California AHMCT Research Center

University of California at Davis

California Department of Transportation

RESEARCH INTO A RAPID ROAD REPAIR MACHINE

Eric L. Schoonbaert

Muthukumaran Arigovindan

Duane A. Bennett

Steven A. Velinsky

AHMCT Research Report

UCD-ARR-03-12-31-01

Final Report of Contract

IA 65A0049 Task Order 02-15

December 31, 2003

This report has been prepared in cooperation with the State of California, Business and Transportation Agency, Department of Transportation and is based on work supported by Interagency Agreement 65A0049 , Task Order 02-15 through the Advanced Highway Maintenance and Construction Technology Research Center at the University of California at Davis.

Abstract

This project researched rapid road repair best practices, analyzed damage scenarios, developed analytical methodologies, and recommends development of a Rapid Road Repair machine.

Current best practices were found to be laborious, costly, and slow. The assessment of damage scenarios provides a basis for understanding earthquake road damage and what damage types can be quickly repaired. After reviewing several ideas for a temporary repair system, this project presents a design concept for a repair structure that can be towed as a trailer to the site of earthquake road damage and deployed as a small bridge over the impassable section of road.

Executive Summary

This project researched rapid road repair best practices, analyzed damage scenarios, developed analytical methodologies, and recommends development of a Rapid Road Repair machine.

Best Practices

Current methods for emergency repairs of roadways are labor intensive, cost intensive and time constrained. During a natural disaster, like an earthquake, the repair on the road needs to be accomplished within certain time limits and it needs to allow for smooth traffic flow over the repair. This may be particularly critical for the mobility of emergency vehicles following such a catastrophic event. This report studies the rapid repair techniques available through the U.S. Air Force based on their need to rapidly repair runways in times of attack.

The U.S. Air Force methods are described including the variety of equipment necessary. The damage expected from an earthquake is also discussed which leads to the need to measure a resultant crater profile to best repair the road. These techniques may be later modified and optimized for various other purposes. Thus available crater profile measurement techniques are also discussed. Since common methods used by the U.S. Air Force include placing mats over the crater, this report develops the analysis methods for a generalized mat structure. The analysis is based on the Finite Element Method. Both conventional aluminum mats as well as composite mats are considered. Through the use of the developed analysis methods, the optimum locations of four supports are identified for a mat with a point load arbitrarily located. Accordingly, this report contributes towards the application of mats to the rapid repair of roadways following a catastrophic event such as an earthquake.

Damage Scenarios

This report discusses the threat that earthquakes present to the road and highway transportation infrastructure, with a focus on road damage caused by surface faulting and liquefaction. A review of earthquake road damage from the Loma Prieta and Northridge earthquakes as well as prediction data for future Bay Area earthquakes provides the basis for understanding the nature of earthquake road damage and what damage types are reasonable repair candidates immediately following an earthquake.

Factors including the damage types, method of use, and geometry considerations are used to develop a set of criteria for the development of a design concept for a rapid road repair vehicle.

Rapid Road Repair Machine

Several ideas for a temporary repair system are discussed and compared to design criteria and road damage scenarios in an effort to determine which design concepts provide the most feasible solution.

The end result is a design concept for a repair structure that can be towed as a trailer to the site of earthquake road damage and deployed as a small bridge over the impassable section of road. A trailer repair structure is attractive because of its simplicity and ease of transportation. Open issues regarding the design concept are addressed and recommendations for further investigation are made.

Table of Contents

List of Illustrations

List of Tables

Disclaimer / Disclosure

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aeronautical Engineering at the University of California, Davis and the Division of Research and Innovation of the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, state and federal governments and universities.

The contents of this report reflect the view of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION and the UNIVERSITY OF CALIFORNIA. This report does not constitute a standard, specification, or regulation.

Chapter 1. Introduction

People in the United States have become accustomed to relying on the large network of roadways at their disposal, but the transportation infrastructure is not only important to individuals, it is also vital to the economic well being of the country. The system of roads is however, not all that robust. Something as simple as a stalled car blocking a lane of traffic can cause major delays during rush hour. Information from the Metropolitan Transportation Commission (MTC) using data from the 2000 Census indicates that in the San Francisco Bay Area over 3 million people commute daily, with about 80% of the commuters relying on their cars for daily transportation (Transportation Related; Transit Commuting, MTC websites). In addition to commuters getting to work, the roadway system is essential to the productivity of many industries. With the roads and highways as important as they are, it is essential that adequate plans be in place to deal with emergency road closures. In California, earthquakes present a constant threat to the transportation infrastructure.

Earthquakes and Road Closures

Disaster relief is a major concern for which a rapid roadway repair would be a significant solution. Studies and previous occurrences show that during an earthquake, cracks along the road or across the road with uneven surfaces are produced. Sometimes the two layers of the soil merge resulting in a distorted surface. Chuckholes do occur if the road was already under repetitive stress. These might be enhanced by the earthquake shocks to develop into larger craters.

The damage caused by an earthquake can take on many forms and have quite varying effects. The damage to the transportation infrastructure can be particularly crippling. Specifically, damage done to roads and highways can impede the evacuation process and keep emergency and rescue vehicles from responding quickly to critical situations. In the worst cases, some areas or neighborhoods might be completely isolated. Currently there is no standardized method for dealing with road damage and each situation is addressed on an individual basis. There exists no crew or machinery whose specific task is to quickly respond to and repair road damage.

Road Closures and Emergency Response

Illustrating the issue of road closures, the Association of Bay Area Governments (ABAG) noted that the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake each closed about 140 roads, many of which remained closed for months (Perkins et al, *Riding out* 7-9). After the Loma Prieta earthquake, the San Francisco International Airport was temporarily closed, not because of structural damage, but because damage to roadways elsewhere in the Bay Area prevented air traffic controllers from getting to work (Perkins, *Don't Wing* 3). The Traffic problems after these two California earthquakes were relatively minor. However major traffic crises and gridlock resulted from the 1995 Kobe, Japan and 1999 Turkey earthquakes. The November/December 97 *Service Matters* newsletter states the following,

> "In fact, there's a better than one-in-three chance that any one of eleven faults will rock the San Francisco Bay Area with a substantial earthquake in the next ten years. Of those, eight have the potential to exceed the damage wreaked on the Bay Area's transportation system by Loma Prieta and Northridge. That's the conclusion drawn by ABAG in its recently released report, Riding Out Future Quakes."

Typical Response

Currently in California the typical response to roadway damage is to first have to the California Highway Patrol arrive at the damaged section and assess whether or not the road needs to be closed. Based on their assessment, the California Highway Patrol will close the road if the damage is severe enough, reroute traffic and then notify the California State Department of Transportation (Caltrans). Caltrans would then send a representative to look at the damage and decided whether to assemble a crew to repair the damage or keep the road closed and contract out a reconstruction effort. Either way the road will be closed at least a few days up to several months, leaving unaddressed the immediate concerns of a closed roadway in the critical hours after an earthquake.

Road Damage

Road damage can have many different causes, anything from sinkholes and natural disasters to the cars traveling on the road and potholes. In addition, not all road damage will necessarily result in a road closure just as not all road closures are caused by impassible driving conditions. The following is a discussion of the types of road closures caused by earthquakes.

Direct and Indirect Causes of Closures

The causes of earthquake road closures can basically be divided into two main categories, direct causes and indirect causes. According to ABAG the direct causes include faulting, liquefaction, earthquake-induced landslides, and shaking damage to bridges and highway overcrossings. The indirect causes include the threat or actual collapse of buildings, the threat of highway collapse on roads, water pipeline ruptures, gas pipeline leaks, hazardous material release and other miscellaneous closures (Perkins et al, *Riding out* 15). During the Loma Prieta and Northridge earthquakes about 45% of the road closures were due to direct hazards and the other 55% due to indirect causes.

Ground Failure

Ground failure road closures include the earthquake road closure types that do damage to the actual road surface. Ground failures are basically a subset of direct causes of earthquake road closures and include surface faulting and liquefaction. The following information on ground failure is from a USGS report on the Northridge earthquake (*Response to an Urban Earthquake* 33).

> “Ground failures include zones of ground fissures and extensional cracking, lateral displacements, settlements with vertical displacements, and compressive deformation in the form of soil and pavement warps and buckles. Ground Failure is used here to describe zones of ground cracking, fissuring, and localized horizontal and vertical permanent ground displacement that can form by a variety of mechanisms (...). In general, ground failure may be caused by (1) surface rupture along faults (...); (2) secondary movement on shallow faults; (3) shaking-induced compaction of natural deposits in sedimentary basins and river valleys, or artificial fills; and (4) liquefaction of loose sandy sediment.”

Faulting

Ruptures along fault lines that cross roadways can cause damage in several different ways. A strike-slip fault can often result in a lateral displacement of the road and can sometimes cause a vertical offset or step. A normal or thrust fault can cause a scarp, a vertical step on the surface of the earth, to occur at a fault. Thrust faults can also cause buckling of the road surface. Lateral spreading at a fault can cause fissures to occur. Extension of the earths crust can cause Horsts and Grabens. A Horst is block of crust between two steep-angled faults that has been raised up while a Graben is a down-dropped block.

Earthquake

Earthquake damages are typically different from that of other road damages. The pavement level might not be as it was before and the unstable ground opens up the highway. Aftershocks, which accompany a large earthquake, are a series of lateral movements of the land. These create fissures and cracks along or across the pavements. Earthquakes often cause liquefaction.

Liquefaction

Liquefaction occurs when water saturated sediment temporarily behaves like a fluid. This can result in ground displacement and lateral spreading; specifically roads and runways can crack or buckle making them impassible to vehicles. The San Francisco Airport (SFO), Oakland International Airport (OAK), and San Jose International Airport (SJC) are in locations that can be susceptible to runway damage due to liquefaction. After the Loma Prieta earthquake, OAK was shutdown due to severe damage to the runway caused by liquefaction.

When liquefied, the stiffness and strength of the soil reduces. Generally, liquefaction occurs in saturated soils, soils near a water reservoir with less shear resistance. The water fills in the space between the layers of soil and exerts pressure on the soil. This pressure increases during an earthquake and causes the soil layers to move with respect to each other. The strength of the soil decreases and maximum damage occurs on the earthquake fault areas. The seismic waves cause these packed structures to behave in a liquefied fashion. The deformation also depends on the type of loading. The deformation occurs due to lateral spreads, flow failures and oscillation of the ground. These develop loose saturated sands on relatively steep slopes, fissures, internal breaks, etc. Gravitational and inertial forces acting on the subsurface causes the top layer of the soil to be displaced laterally. Prior information about the susceptible areas is available as liquefaction potential maps. Construction procedures such as blasting also triggers increases in water pressure. Some of the earthquake damages and liquefaction are shown in the following pictures.

Figure 1 Earthquake damages on Roadways

Past Earthquakes and Future Closure Models

The Association of Bay Area Governments (ABAG) is a regional planning agency that works with problems concerning land use, housing, environmental quality and economic development in the greater San Francisco Bay Area. ABAG's region includes the counties of Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma, a region of about 18,130 square kilometers [7000 square miles] and over 6 million people. Because of ABAG's role as an association of cities and counties, state and federal governments have designated ABAG as the official comprehensive planning agency for the Bay Area. As such, one of the major health and safety issues is earthquake preparedness (ABAG Overview website). ABAG publishes geology and shaking hazard maps for the Bay Area. Much of the following has come from their reports on past earthquakes and their road closure models.

Loma Prieta and Northridge

The road closure statistics for the 1989 Loma Prieta and 1994 Northridge Earthquakes are remarkably similar. The Loma Prieta Earthquake closed 142 roads with 46% of them due to direct causes and the Northridge Earthquake closed 140 roads, with 45% of them due to direct causes. Although the damages to the transportation systems were similar, in other areas such as damages to housing, the Northridge Earthquake was far more severe, doing more damage. Generally, for both earthquakes, the severity of the road damage due to direct causes was higher. Of the 128 total road closures for both earthquakes due to direct causes, 40% were impassable while only 11% of the 159 road closures due to indirect causes were impassable.

For both earthquakes, the damage to freeways and highways was significantly different than the damage to streets. Overall, freeways and highways were less likely to be closed than streets with only 78 freeway and highway closures, compared to 204 street closures. The majority of freeway and highway closures, 68 of the 78 total, were from direct causes, while direct causes made up only 60 of the 204 total street closures. In general the damage to freeway and highways was more severe with 46% of the closures impassable while only 16% of the street closures were impassible. This trend fits along with the data indicating that direct causes of closures tend to involve more road damage.

Among direct causes of closure, shaking damage was the leading cause of road closure, followed by landslides and liquefaction. Faulting accounted for none of the closures in either earthquake and liquefaction made up 12% of the total closures in Loma Prieta and 7% of the total closures in Northridge. A summary of all of the data can be seen in the following table, taken from the ABAG report *Riding out Future Quakes* (7-10).

Loma Prieta and Northridge Earthquake Road Closures

	Hazard Type	Loma Prieta		Northridge		Loma Prieta and Northridge			
		No.	% of Total	No.	% of Total	Freeways Highways	Streets	Total	% Impas-sable
Direct Hazards	Shaking	30	21%	31	22%	49	12	61	44%
	Landslides	23	16%	22	16%	16	29	45	53%
	Liquefaction	17	12%	10	7%	7	20	27	15%
	Fault Rupture	0	0%	0	0%	0	0	0	0%
	Total Direct	**65**	**46%**	**63**	**45%**	**68**	**60**	**128**	**40%**
Indirect Hazards	Building Damage	43	30%	15	1%	0	58	58	2%
	Fwy Hazard	15	11%	13	9%	0	28	28	50%
	Nat. Gas Release	0	0%	7	5%	0	7	7	14%
	Haz. Mat. Release	0	0%	3	2%	0	3	3	0%
	Water Main Breaks	17	12%	18	13%	0	35	35	6%
	Other	3	2%	13	9%	0	16	16	6%
	Traffic Control	18	13%	10	7%	10	18	28	0%
	Total Indirect	**82**	**58%**	**77**	**55%**	**10**	**149**	**159**	**11%**
Closure Reason	Public Safety	109	77%	104	74%	42	171	213	
	Impassable	33	23%	36	26%	36	33	69	
	Total Closures	**142**	**100%**	**140**	**100%**	**78**	**204**	**282**	

Table 1 Loma Prieta and Northridge Earthquake Road Closures

Prediction of Future Closures

The 1997 ABAG report *Riding Out Future Quakes* contained extensive information about road closures in the Bay Area due to both direct and indirect causes based on earthquake scenarios along different Bay Area faults (123-70). The predictions were based on analysis of data from past earthquakes and ground shaking intensity models. In 2003, using updated models, ABAG released new estimates for the number and location of road closures due to earthquakes along major Bay Area faults. The data, found on their website (ABAG Earthquakes), can be shown in terms of closures by county or by closure cause.

Although during the Loma Prieta and Northridge Earthquakes direct causes made up less than half of the road closures with none of the closures due to faulting, the 2003 ABAG predictions for future road closures associated with major faults in the Bay Area predict that two direct causes of closure, faulting and liquefaction, combined will constitute between 20% and 35% of the closures. Predictions for the worst cases show that a major earthquake along the entire length of the San Andreas Fault would close an estimated 1,332 roads with 217 closures due to faulting and 73 due to liquefaction. An earthquake along the entire Hayward Fault would close approximately 1,734 roadways with 520 closures due to faulting and 91 due to liquefaction. One thing to note about the predictions is that road closures do not necessarily mean the condition of the road are impassible. About 40% of the road closures from the Loma Prieta and Northridge earthquakes due to direct causes had impassible conditions. The following table contains the numbers for predicted road closures for earthquakes along other faults in the Bay Area.

Predicted Number of Road Closures for Future Bay Area Earthquake Scenarios

COUNTY	Predicted Magnitude	Total No. Road Closures	No. Due to Faulting	No. Due to Liquefaction	Combined	% of Total
San Andreas – S. C. Mts.	6.9	154	25	7	32	20.8
S. A. - Peninsula-G. Gate	7.2	866	163	40	203	23.4
S. A. - N. Golden Gate	7.5	581	29	29	58	10.0
S. A. - Entire Bay Area	7.9	1332	217	73	290	21.8
No. San Gregorio	7.2	401	58	22	80	20.0
Southern Hayward	6.7	1138	346	66	412	36.2
Northern Hayward	6.5	667	174	29	203	30.4
N + S Hayward	6.9	1734	520	91	611	35.2
Rodgers Creek	7.0	402	82	32	114	28.4
Rodgers Creek – N. Hayward	7.1	1084	256	58	314	29.0
Southern Maacama	6.6	74	22	2	24	32.4
West Napa	6.5	159	45	8	53	33.3
Concord-Green Valley	6.7	386	102	27	129	33.4
Northern Calaveras	6.8	363	84	41	125	34.4
Central Calaveras	6.2	210	27	15	42	20.0
Mt. Diablo Thrust	6.7	228	0	21	21	9.2
Greenville	6.9	138	25	9	34	24.6
Monte Vista Thrust	6.6	326	111	16	127	39.0

Table 2 Predicted Number of Road Closures for Future Bay Area Earthquake Scenarios

Airports At Risk

ABAG released a report in December of 2000 on Bay Area Airports and earthquakes entitled *Don't Wing It* (Perkins). The report lists four categories which future earthquake threats fall into, liquefaction damage to airport runways, shaking damage to structures, power and communications disruptions, and disruptions to the transportation systems serving the airport. The issues associated with two of these categories, the runway liquefaction and the disruptions to the serving transportation system, could be addressed with a Rapid Repair machine.

Current Response and Repair Procedures

The California Highway Patrol (CHP) and Caltrans have an established set of emergency responsibilities following a major earthquake. These responsibilities include providing up-to-date information, traffic control, damage assessment and long term recovery planning. Generally, the CHP is responsible for short-term traffic control until Caltrans arrives and is able to take over (Perkins et al, *Riding out* 120).

Caltrans' Emergency Responsibilities

Among Caltrans' responsibilities after an earthquake are planning and implementing long-term traffic control and evacuation plans in cooperation with the CHP. Obviously one of Caltrans' goals is to re-open damaged state transportation system components as soon as possible. This includes establishing route recovery plans, emergency contracting for highway reconstruction and providing engineering and technical assistance to the Office of Emergency Services (OES) and other State and local government agencies relative to transportation services (Perkins et al, *Riding out* 119).

Repair Procedures

Once a damaged section of road has been reported to or discovered by the CHP, they will inspect it and make a judgment on whether or not to close the entire road. If it appears as though it will take more than about an hour to open the road, traffic will be diverted and Caltrans notified. Caltrans will follow up by sending someone to assess the damaged section of road. Based on the extent and location of the damage and the importance of the road, Caltrans will decide on appropriate actions, which could include keeping the road closed for eventual rebuilding, scheduling emergency contracting for reconstruction, or deploying workers to immediately begin clearing the road for through traffic. The situations are generally dealt with on a case-by-case basis, as there is no standard protocol. The first two types of responses, eventual rebuilding and emergency contracting, are longer-term solutions to the closed road that could take from a few weeks to many months to complete. Having Caltrans workers immediately start clearing and resurfacing the road could allow it to reopen to traffic in anywhere from less than a day to a few weeks.

Rapid Repair Concepts

Current methods for emergency road repairs are labor intensive and they are not normally preplanned well in advance. No proper concept exists to repair a damaged pavement within certain time limits. The infrastructure and technology for these processes need to be more advanced to handle emergency situations.

Smooth transportation over the highways is of the major concern for commerce as well as emergency services. In the event of a catastrophic pavement damage for which the vehicles cannot pass, a repair is needed quickly. This repair can either be a temporary repair or a permanent one. In either case, a rapid repair is required so that emergency vehicles can pass as soon as possible.

When it comes to quickly repairing a section of earthquake-damaged road, there are a few things to think about. First, all of these concepts are for situations where the damaged road section is critical enough that Caltrans has decided they cannot wait for the road to be rebuilt. Second, the main goal of rapidly repairing the road is to open the road immediately to traffic, so the following concepts all place emphasis on opening a closed road. All of the concepts have a couple of traits in common. They have some way of creating a course so that a vehicle may pass through what would have otherwise been an impassable section of road, and they are more mobile and can respond sooner than a typical repair contractor.

Quick Construction Team

A Quick Construction team is basically a team of individuals using conventional construction equipment who can quickly respond to road damage. This is similar to military RED HORSE Squadrons (RED HORSE is an acronym for Rapid Engineer Deployable Heavy Operational Repair Squadron, Engineer), which perform highly coordinated runway repairs and construction. An advantage of using this method is that it does not require specialized machinery and uses equipment that Caltrans possesses. Some of the drawbacks concern the complications associated with transporting the equipment to the site and coordination among the different personnel.

Road Cover

The Road Cover idea involves using a structure to cover up or bridge over damaged road sections, similar to construction trench covers. What makes this a rapid road repair concept is the ability for the transportation and deployment of the cover structure to be done by a single or very few vehicles. The main drawback of this concept is the potential exclusivity of the machinery. With such specialized equipment it is very likely it would sit idle most of the time until an earthquake or other emergency situation.

Road Fill

The idea behind the Road Fill rapid repair concept is to use some sort of material to fill in or cover damaged sections of road. What makes this concept different than the Road Cover concept is instead of using a structure to cover the damage, this would use concrete or a similar material to fill in and cover the damage. Like the Road Cover concept, a single or very few vehicles can do the material transportation and filling. Also similar to the Road Cover concept, the main downside to this concept is its likely specialization of machinery, limiting its use to emergencies and earthquakes.

Selecting the Most Viable Concept

Each of the previously described concepts has its strengths and weaknesses, so selecting the best concept to fully develop is not a simple straightforward choice. In order to make a selection between the concepts some general repair parameters need to be developed by which the concepts can be compared. These parameters will also be carried throughout the conceptual design process, being refined and added to as the design concept develops.

General Repair Parameters

The nature of earthquakes and emergencies are that nobody knows when or where they will occur. A likely scenario is that the equipment for the rapid road repairs will be stored at several Caltrans equipment yards around the state of California, waiting to respond to situations as needed. This brings up two very important points about the machinery as follows. If highly specialized, it could spend the majority of its time sitting in an equipment yard, and when it does come time for it to be used, it needs to be able to get to the site of the road damage. The mobility of the machinery is one of the key features to quickly opening a damaged road. Because of the equipment downtime issue, it is desirable to have equipment that has more than one use or does not require its own specialized vehicle, which is expensive.

The equipment has to be reliable, because as previously noted it may not be used very often, but when it does come time for it to be put into action, it needs to work. This means it is reliable not only in its operation, but also that long periods of inactivity will not negatively affect its functioning. The equipment also needs to be self-contained and not rely on any external sources of power or water or anything else. This is obvious because after an earthquake or any emergency situation these resources may not be available and cannot be depended upon.

In general, it is best to accomplish the repair with the minimum number of pieces of machinery and personnel. Concerning personnel, the operation of the equipment should be simple enough not to require highly trained or specialized operators, so that anyone familiar with the equipment could get the job done. Again, in order to have this equipment at multiple locations, the cost has to be reasonable. To make this a rapid repair, the time it takes for the operators to complete a repair from the time of their arrival at the scene to reopening the road should be as quick as possible. The general repair parameters for the repair machinery and equipment are listed in order of importance.

General Repair Parameter for the Repair Apparatus

1. Transportable and mobile
2. Effective at opening damaged roads
3. Versatile in setup or has a non-specific use
4. Reliable and robust even after long inactivity
5. Self-contained requiring no additional hookups (power, water, etc)
6. Comprised of the minimum number pieces of equipment
7. Requires the minimum number of operators
8. Operates with non-specialized personnel

9	Low enough cost to have at several locations
10	Quick completing the repair

Table 3 General Repair Parameter for the Repair Apparatus

Comparison of Concepts to Parameters

The Quick Construction Team concept has its main weakness in the area that is probably the most important, transportation. Considering there will have to be more than one piece of equipment going to the site of the road closure, and that nearly all of the construction equipment must be transported by a separate vehicle, the transportation can become quite complicated. By contrast both the Road Cover and Road Fill concepts are mostly self contained and could be transported to the road closure with a single vehicle or under their own power.

All three of the concepts should be able to effectively open damaged roads but the Road Fill concept is probably at a bit of a disadvantage. It uses a concrete or similar substance to fill or cover the damage. This would work fine in areas of liquefaction and extensional or lateral cracking, but would be less effective in dealing with fault scarps and buckling or other types of damage with vertical features. Both the Road Cover and Road Fill concepts would also encounter more difficulty as the repair surface steepness increased.

The versatility of the Road Cover and Road Fill concepts depends largely on their final designs, but even in their most versatile incarnations they would probably still find less use than the conventional construction equipment. The next two parameters, reliability and self-containment are more of design constraints and do not factor in so much during the concept comparison stage

Having the minimum number pieces of equipment and minimum number of operators is another area where the Quick Construction Team is at a fundamental disadvantage. This concept involves several pieces of equipment and operators working together. The Road Cover and Road Fill concepts on the other hand focus on placing only one or two essential vehicles at the site of the road damage. The skill level required to operate the equipment and accomplish a repair is probably similar for all three of the concepts. Although the Quick Construction Team concept uses conventional construction equipment that requires trained operators, there are already many people qualified to do the job. The Road Cover and Road Fill concepts will need to have people trained in their use but the intention is to have the operation as intuitive as possible so that the training would be minimal.

Stocking equipment yards with equipment that will not be used often is an expensive prospect, especially when the pieces of equipment are entire vehicles. The Quick Construction Team concept alleviates some of this expense problem by having equipment that has alternate uses besides rapid road repair, in fact much of the equipment would just be general construction machinery. The Road Cover and Road Fill concepts do not have very many other uses besides emergency situations, making the cost per use for their equipment higher. To offset this, the concepts focus on designs that do not require entire dedicated vehicles.

Considering which concept is likely to be the quickest at reopening a damaged road to through traffic based on the concept idea alone is clearly only an estimate. One concept might be slow for a certain type or size of repair but faster for another. That said, the repair concept that will have quickest time, from equipment arrival at the damaged site to when the first vehicle can pass, is probably the Road Cover concept. This is because it takes the least amount of preparation time to simply lie down and secure a structure to cover the road damage. The Road Fill concept is probably the next fastest repair concept. The reason this concept is probably slower than the Road Cover is because it relies on a medium that must dry or cure and the Road Cover concept does not. This could become an issue when the repaired section must dry before another section can be reached. The Quick Construction Team concept is probably inherently the slowest because it requires the completion of the most steps in its repair process. Using conventional construction equipment requires the orchestration of each piece of equipment, which is meant for one part of the repair.

Best Practices and Analysis

The basic idea of this project is to suggest a reliable, high quality, temporary repair under any road damage conditions. First, a vendor search was made through the web pages and with the OES (Office of the Emergency Services) and the California Department of Transportation (CALTRANS). No predefined concept used for implementing the temporary repairs was found. A typical procedure is as follows. Data is collected from the damage site and then it is processed by higher-level personnel, where the method of repair is determined based on their experience and a set of protocols. These protocols do not comply for rapid repair criteria, as the operations are actually maintenance implementations and traffic is either diverted or ceased for these operations.

In the defense field, the rapid construction and repair of both roadways and airport runways has been investigated for many years. Accordingly, based on the similar scenario for earthquake damaged public highways, a search was conducted of rapid repair methods used in the defense field. The nature of damage may be different, but the basic idea of rapid recovery complies for us to define a set of protocols based on a strong concept for these road repairs.

The numerous methods available under the Rapid Runway Repair (RRR) program of the US Air Force, gives a brief idea of potential approach for the road damage repairs. A detailed study of the Rapid Runway Repair methods is thus presented in a later chapter.

This report discusses the available, possible rapid runway methods used by U.S. Air Force bases to counteract a situation when the enemy damages the runways. These concepts are analyzed so that these potential methods can be modified for the rapid roadway repair process. The report also analyzes a plate structure, which is the primary model of the mat that will be used as a temporary pavement over craters. In order to simulate actual mat conditions, the conventional honeycomb mat is also analyzed in further chapters. To simulate the behavior of the plate structure, analysis based on the Finite Element Method is performed. The results are later analyzed for optimum support conditions in later chapters. Optimization of the boundary conditions is a critical phenomenon, as the parameters such as diameter, depth, soil strength, etc, of the crater damage are not pre-defined and vary during every damage condition.

The report analyzes the concepts available for different processes but which can be applicable for emergency methods and also analyses the mat structure, which is the prime model that is used to repair these damages.

Summary

This section illustrated some of the damage to the road highway networks that has been caused by previous earthquakes. It also covered predictions for future road closures due to fault ruptures in the Bay Area. Past experience and these predictions suggest the need to develop methods and equipment for rapidly repairing earthquake damaged roads and a plan for implementation. With the need for a repair system established, different repair concepts were introduced and compared to a set of general repair parameters. From this, the Road Cover concept was selected to be the basis for the conceptual design of a rapid road repair vehicle.

Chapter 2. Study of Rapid Runway Repair

Techniques Used for Rapid Runway Repair

A detailed study on the current Rapid Runway Repair (RRR) methods was done as a major part during the period of research to obtain a strong basic knowledge of the process and its concepts.

The Rapid Runway Repair method is a technique that is used by many organizations to protect one of their critical assets, their airfields, for combat support mission aircraft operations, maritime patrol operations, etc. For smooth traffic flow, these organizations need to ensure a quality repair. No real database of the damage and procedures are available at present. However, detailed study of the method shows that the damage assessment, minimum operating strip calculation, repair quality criteria and rapid runway repair are the significant concepts that are being used conventionally. Currently, there are few methods available that are being followed to achieve Rapid Runway Repair. The nature of the damage is quite different from that of the conventional runway damage like potholes, etc. Hence, each method is personalized for each type of damage incurred.

In order to classify the RRR methods, the System Analysis approach has been used. This approach is defined as a concept to look at set of problems with an analytical inquiry that can help us make the right decision in selecting the method according to the damage incurred and parameters available. The analysis done previously in the USAF manuals show that this method had been used intensively and provide an idea for any runway/pavement damage repair. The damages vary but the solution to be provided can share the same concept, which should be a rapid, efficient way to provide a best quality repair, but a temporary one in the case of emergencies. In addition, the rapid runway repair process deals with analogous damage conditions a roadway would be subjected to, and the RRR team follows certain steps and procedures to achieve an immediate and reliable solution for the damage repair.

The U.S. Air Force flies and fights from its air bases during a war and it is at these air bases that air power is most vulnerable. Under certain circumstances, air bases can be a most immediate and remunerative target for an adversary. It seems to be more effective to destroy aircraft while they are on the ground than to hunt them in the air. From a pragmatic perspective, it is reasonable to say that during some phase of a conventional conflict, the repair of airfield pavement damage will be one of the civil engineer and his team’s essential wartime missions. Repair of these airfield damages can be a complex and difficult task requiring the involvement of heavy labor and heavy vehicles with good coordination. Proper preparation must be accomplished prior to the moment of need. Time would not be available during a conflict to develop a concept and implement it to repair.

In order to ensure the airfields can return quickly to their active operational role following an attack, a well-organized rapid runway repair effort is crucial and thus effective Rapid Runway Repair planning and practice is necessary. Several important issues of RRR are described below.

Normally, RRR resources are dispersed to protect locations on a base. Current requirements suggest that RRR assets should be dispersed to no less than three separate sites. Equivalent items should be administered to each of the different dispersal locations to improve the probability that some resources are usable whenever repair is essential.

Following an attack, damage assessors provide information about the location and extent of damage to the surfaces of the airfield. The wing operations center would collect other critical information on operational requirements and expected operating conditions following the attack. Once this information is obtained, the minimum operating strip (MOS) selection team would select the operating strip that needs a repair for restoring normal air traffic. After approval of the MOS by the wing commander, explosive ordnance disposal teams would work on those areas that have been designated to them. The MOS selection team would finalize the repair quality criteria (RQC) for all repair patches on the MOS. The RRR teams then would move to the runway and taxiway repair locations and deliver appropriate repair activities.

Selection of the MOS, and determination of repair quality criteria are important procedures during the RRR. Detailed procedures for crater repair using several types of fill material as well as step-by-step instructions including the installation of the folded fiberglass mat and AM-2 mat foreign object damage (FOD) covers are discussed in the later part of this chapter.

Expected Damage

The scope of airfield operating surface repair requirements will vary proportionally to the intensity of an attack. It could range from debris clearance with little pavement disruption, if any, to major airfield damage accompanied by complete shutdown of aircraft launch and recovery activity. The latter must be prepared for and must be handled swiftly and correctly. Normally, when there is major airfield damage, numerous spall fields are expected. The RRR team should overcome these multiple problems and provide an accessible and functional MOS within as short a time period as possible. They may be required to accomplish the work at night, in rain or snow, or even in a chemically contaminated environment, which makes the job complex and threatening for the team members.

During wartime or contingency operations, the scope and depth of the RRR team’s task would vary widely. The flexibility within the units to be able to respond to these tasks at any time should be with sufficiently capable personnel. Wartime tasks cannot be expected to show the skill mix of these units at all times; therefore, they should develop an inherent flexibility to cross boundaries when faced with shortages of specific skills and sizable wartime requirements and perform the repair. Each of them must be able to perform tasks outside of their normal peacetime responsibilities if they are to properly support their combat forces as what the team should be prepared for. Multi- skilled labor is very essential during RRR for equipment operations, which indicates labor intensiveness.

The damage type of the crater were categorized as

1.Spall

2.Small Crater

3.Large Crater

The MOS is determined with respect to the damage type incurred. The crater classifications are shown in the following.

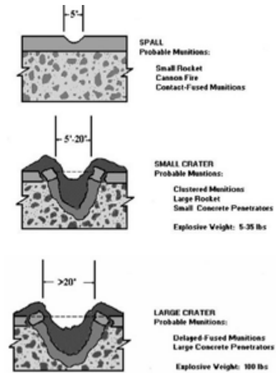


Figure 2 Categorization of the pavement damage [USAF Manuals]

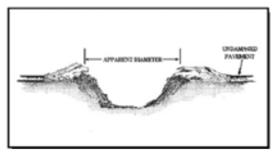


Figure 3 Crater damage [USAF Manuals]

Craters are classified with respect to their apparent repair diameter. If the damage is measured less than 1.5 meters in diameter it is referred to as a **Spall**. If the pavement damage from conventional weapons which results in pavement upheaval around the crater and an apparent crater diameter of less than 6 meters, it is referred to as a **Small Crater**. The pavement damage caused by conventional weapons that penetrate the sub grade and have the ostensible crater diameter greater than 6 m is called **Large Crater**. For earthquake damages, the crack width is to be considered for repair with similar classification as of craters to determine the minimum operating strip for repair.

Crater Profile Measurement (CPM)

This is a technique used to determine how much of up heaved pavement must be removed at the beginning of the crater repair. This method is an integral part of RRR technique and is done before and after the repairs. CPM is a small but critical process to ensure smooth operating surface. On a runway, the aircraft cannot operate on a rough operating surface. Rough surfaces create vibration throughout the airframe and especially on the landing gear.

Craters very rarely have an equal amount of upheaval amount around them. During RRR, stanchions and a rod measure extent of upheaval. Up heaved pavements will interrupt the line of sight between the two stanchions. If the repaired surface falls between plus or minus 0.02 m [¾”] from the original pavement surface, it is considered a Flush Repair. Two stanchions with sighting plane are positioned on either side of the crater. The bubble level on the stanchions determines the pavement surface where the stanchions are placed. The rod consists of three triangular plates, one single non-moveable template target, used to identify initial upheaval and intermediate profile check to identify complete upheaval removal. The other end of the rod has two slide template targets for quality control checks. They can be moved closer together or farther apart.

The measurement method is subdivided and executed in the order of:

Initial Profile Measurement,

Intermediate Profile Measurement,

Final Profile Measurement,

Maintenance checks.

Initial Profile Measurement Process

The stanchions are placed parallel to the centerline of the runway/roadway and inline with the approximate center of the crater. This configuration is referred as sight line or lane. The stanchions are placed on the clean sound pavement and the distance between them depends on the size of the crater and they do not reflect the upheaval of the crater and is the reference level.

The rod is placed, vertically with moveable triangle upward, in between the stanchions and viewed from one of the stanchions. If the rod triangle interrupts the view, then upheaval is present. The rod is moved 0.6 m [2 feet] – 0.9 m [3 feet] nearer to the main stanchion and checked for upheaval. If the triangle falls down from the line of sight between the stanchions, there is no upheaval present.

The pavement is marked 0.6 m [2 feet] away from the rod and towards the stanchion using spray paint, or a marker depending on the environmental conditions. The approximate value of the upheaval distance for a crater diameter of 6 m [20 feet] is normally 1.5 m [5 feet]. The amount of fill material is calculated on these parameters. The crater is divided into four segments and lines at equal intervals of 1.5 m [5 feet] and parallel to the centerline. The stanchions and the rod are placed on the adjacent lines and approximately 0.9 m [3 feet] from the crater area and the Line of Sight technique is performed and the pavement is marked where is the upheaval is detected. This process is done until one segment is completed and similarly the process is repeated in other segments. The marks are later joined for the repair to be done as shown below. The following figures show the stanchion and the targets with their measurements.

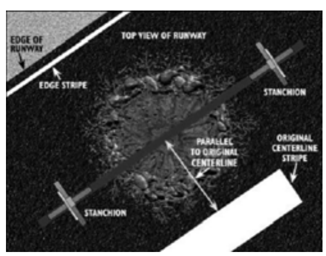


Figure 4 Top View of the Crater damage site [Crater Profile Measurement, 1998]

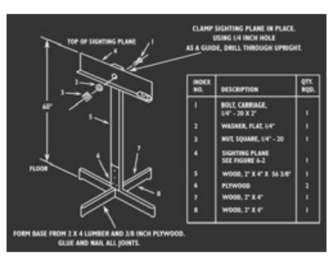


Figure 5 The Sighting Plane [Crater Profile Measurement, 1998]

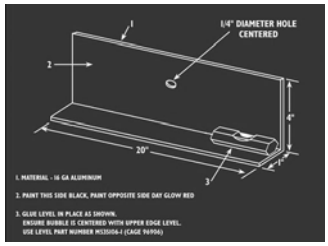
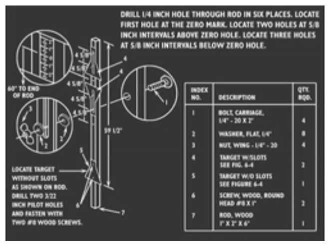


Figure 6 Top of Sighting Plane [Crater Profile Measurement, 1998]



INDEX NO.	DESCRIPTION	QTY. RQD.
1	BOLT, CARRIAGE, 1/4" - 20 X 2"	4
2	WASHER, FLAT, 1/4"	8
3	NUT, WING - 1/4" - 20	4
4	TARGET W/SLOTS SEE FIG. 6-4	2
5	TARGET W/O SLOTS SEE FIGURE 6-4	1
6	SCREW, WOOD, ROUND HEAD #8 X 1"	2
7	ROD, WOOD 1" X 2" X 6'	1

Figure 7 Target Rod [Crater Profile Measurement, 1998]

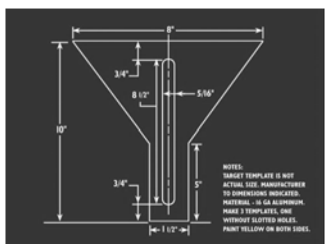


Figure 8 Top Target [Crater Profile Measurement, 1998]

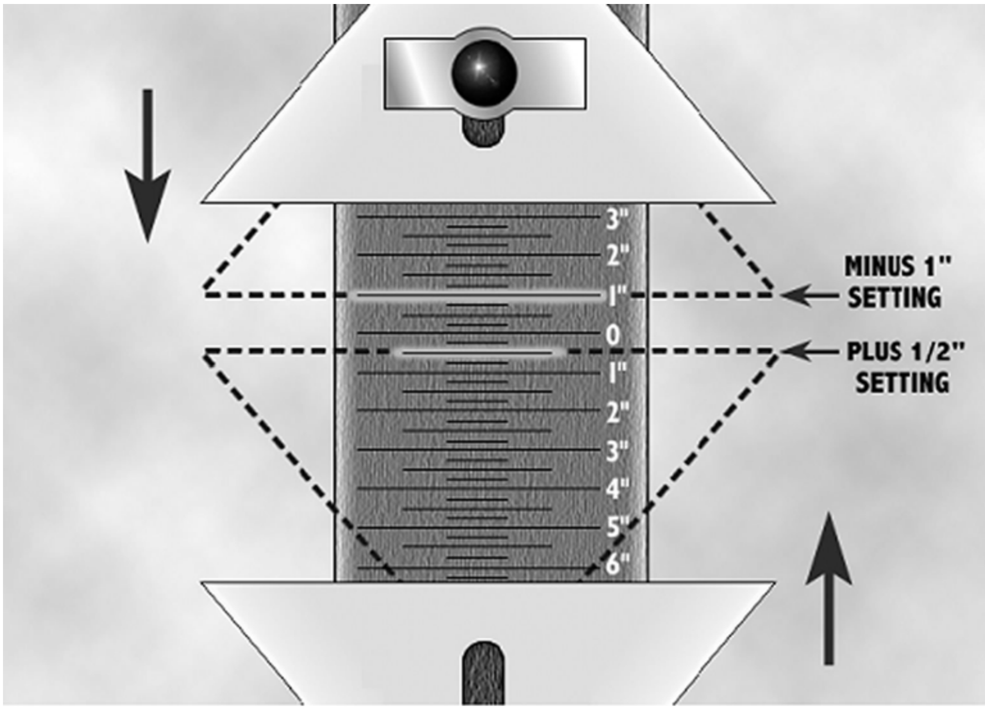


Figure 9 Adjustable Targets [Crater Profile Measurement, 1998]

Intermediate and Final Measurement

The intermediate and final crater profile measurements are similar to that of the initial crater measurement process and are performed once the upheaval is removed. The rod with single triangle is positioned at the top and placed on the other side of the crater, away from and facing the main stanchion. It is placed at the tip of the crater and the process is executed. If the target interrupts the line of sight, then it implies that the upheaval is present and the target is moved by 0.3 m away from the crater and checked until no upheaval is detected. If upheaval is found, the repair is done again.

Sometimes the processes are performed more than once due to presence of upheaval even after the initial processes. The failure to remove the upheaval is due to one of the following three reasons:

- Inaccurate identification,
- Improper upheaval removal during repair,
- Damage by the repair vehicle. For example, the front-end loader bucket with teeth causes more upheaval.

If no upheaval is present then fill material should be brought, compacted, and leveled until the repair surface levels the surrounding pavement.

For final profile measurement, the dual triangle target end is used. To meet flush repair criteria, the rod's actual measurement setting would be + 0.01 m [1/2 inch] to a –0.025 m [-1 inch]. These settings allow for the 0.03 m [1 ¼"] thickness of the FRP mat cover. Some allowance should be provided across the widest part of the triangles by placing a red tape or paint, 0.006 m [¼"] stripe. The stanchions are once again positioned with respect to the centerline and the rod is placed between them. It is then positioned on the repaired area approximately 0.6 m [2 feet] from the crater edge. This process is done along five parallel lines, 0.05 m [2-inch] to 0.07 m [3-inch] apart from the neighbor line. If the target falls in the 0.03 m [1.25-inch] - red zone during the process for three consecutive measurements or more, the repair exceeds the flush criteria. If one measurement falls outside the 0.03 m [1.25-inch] - red zone, then it exceeds the flush criteria. If this occurs, the crater has to be re-repaired.

The Repair Quality Criteria system is used to calculate the allowable repair roughness using different charts and tables. In different weather-runway conditions, the crater becomes serviceable even if it falls below the flush repair criteria with respect to the Minimum Operating Strip and Repair Quality Criteria. The final crater measurement is repeated for every re-repair.

RRR Methods and Procedures

The methods used for Rapid Runway Repair are classified based on the FOD cover being used for the repair as they define the procedure and fill material for the crater. These methods are used as the base condition to develop a concept for the rapid highway repairs.

Conventional Methods

There are nine Rapid Runway Repair mats and techniques to deploy them.

Fiberglass – Reinforced Plastic (FRP) mats

These types of mats are made of 2-3 plies. Mats of different sizes are available. The craters are backfilled with debris available surrounding the crater. It is then filled with crushed rock and compacted to the pavement level. The FRP mats are towed, positioned and bolted on to the pavement surface. A polymer concrete ramp is constructed on the mats leading edge for smooth operation of traffic. This mat technique assumes dry conditions.

Bolt-Together FRP mats

These types of mats are made of 3 plies. They are identical panels, which are bolted together at the crater site.

Foldable FRP mats

These mats are made of 2 plies. The panels are joined along the edges. They are impregnated with flexible polyurethane. The mats can be cut or glued according to requirements.

Precast concrete slabs

Portland cement concrete, 2 m x 2 m x 15 m, is used. The debris is removed. The concrete is sawed and cut to obtain a square or rectangular geometry. The crater is filled with ballast rock and gravel to level to about 0.1 m [4 inches] below pavement level. Then, the Precast Concrete Slab is placed and compacted using a roller.

Precast asphalt concrete block

Asphalt concrete blocks, of size 0.6 m x 0.6 m x 0.1 m [24 inches x 24 inches x 4 inches], are used. The same procedures of backfilling with debris and later with crushed rock are done. Compaction is done depending on the block thickness. The slabs are then placed and heated with an infrared heater for compaction. Again, they are leveled and compacted.

Magnesium Phosphate mats

Magnesium Phosphate cement of high controlled early strength is used. They have formulated non-shrinking grout to penetrate the voids. The crater is filled with ballast and graded stone. The grouted crushed rock is then positioned and placed. These mats are suitable for different weather conditions.

Crushed Rock

This method does not use a Foreign Object Damage (FOD) cover. It requires very high quality well-graded crushed rock. Backfilling with existing debris is done and filled with crushed rock. Compaction is done to complete the repair.

Polyurethane cap (fiberglass mat)

This method uses polyurethane grout. A rapid setting, high strength polymer concrete surface can be achieved. The crater is backfilled, filled and leveled with gravel. The Polyurethane concrete is applied and continued filling until percolated concrete is even on the crater surface. This method needs five minutes for setting and is ready for traffic.

AM-2 Aluminum mats

These FOD covers are fabricated aluminum panels. They have the same procedures as the FRP mat crater repair technique.

Previous studies have shown that there is intensive equipment usage for repair tasks. Harsh external conditions may also hinder the repair process and it is important to choose the repair technique that could provide the best performance and a high degree of success. RRR is a labor-intensive operation and varies depending on the method chosen. The methods need to be less complex, which may lead to greater potential for unforeseen difficulties and errors. Structural strength is the important factor that ensures a successful repair. Maintenance of these repairs, as discussed before, should be checked for ruts, loose bolts, damage on mats and repairs periodically. Repair time for RRR applications is critical and so is always kept to a minimum. Other conditions like storage and shell life are also considered.

Foreign Object Damage Cover Installation

There are two types of FOD Covers preferred for RRR Operations, Folded Fiber Reinforced Plastic Mats, and AM-2 Aluminum Mats.

AM-2 Aluminum Mats

The AM-2 Aluminum panel is a hollow honeycomb aluminum panel of 0.04 m [1 ½”] thickness. These mats are laid down in a continuous layered fashion and connected together by end inside connectors. The complete patch is 16 m wide by 23 m long [54 feet by 77 feet 6 inches]. The mats are towed over the crater and ramps are attached to the ends of the patch. The drawback of the aluminum mat is that a bump caused due to the thickness can impart significant damage on the aircraft or vehicle. When these mats are not placed close together, it causes structural damage to the aircraft or vehicle. This mat laying process involves intense manpower. It has 175 separate mat panels and 18 ramp panels that must be laid and connected to form the patch. Am-2 Mats are used in Taxiways and parking aprons in airbases.

Folded Fiber Reinforced Plastic Mats

The Folded Fiberglass Reinforced Mats weighs up to 136 N [3000 pounds] and consists of nine fibreglasses 0.006 m [0.25-inch] thick panels. The panels are connected by elastomer hinges, which are 3 inch wide in folded condition. The FRP mat is 1.82 m [6 feet] wide and 9 m [30 feet] long and 0.2 m-0.25 m [8-10 inches] thick. Two mats are normally required to cover the crater area. Using a joining panel results in a 16 m x 18 m [54’ x 60’] patch that connects the mats. The folded FRP mat is preferred for Minimum Operating Strip Foreign Object Damage cover, if the crater is initially filled. Since the mat is 0.006 m [¼”] thick, it imparts less vibration on the aircraft or vehicle. These mats are easy to deploy, assemble and they are air transportable. The mat is usually assembled, pulled over to the crater area and anchored to the pavement.

Rutting is one of the problems that occur when a FRP mat is used for crater FOD cover. Rutting is caused by the vehicle tire, which causes a compression and shift of the filled material below the mat. Rut depths are determined by the final profile measurement line of sight technique to check if it falls within the Repair Quality Criteria tolerances. Due to mat rigidity, rut area cannot be determined. A load can be applied on the mat that can help in identification of the rut area. Normally a vehicle like truck can be allowed to pass to identify the rut area with respect to the RQC tolerance. If the repair is critical, then the FOD cover should be removed for further repairs. Regrading and recompacting should be done during maintenance repairs. Loosened anchor bolts and torn fiberglass should also be checked periodically.

In order to achieve expedient repairs to war damaged airfield pavements, engineer forces require proper equipment and adequate personnel. To satisfy these requirements, the Air Force has some developed equipment sets for accomplishing airfield pavement repairs. Moreover, Air Force civil engineering teams such as Prime BEEF (Base Engineer Emergency Force) seem to have been designed to provide sufficient numbers of personnel to adequately run these equipment sets. There are many civil engineer teams involved in these processes, each allotted certain operation.

RRR Equipment Sets

The RRR equipment set is a standardized set of equipment and vehicles that enable civil engineer forces to conduct RRR. At present there are three RRR sets that have been fielded by the organization. The sets are configured in a unit manner to provide an assigned crater repair capability. The following shows the basic equipments used for RRR operation.

Vehicles	Quantity
Excavator	3
Grader	3
Dozer (T-7)	3
Front-End Loader (4-cy)	6
Front-End Loader (2.5-cy)	3
Vibratory Roller	3
Dump Roller (8-cy)	8
Dump Roller (5-ton)	4
Tractor (7.5-ton)	3
Tractor (10-ton)	3
Trailer (22-ton)	3
Trailer (60-ton)	3
Vacuum Sweeper	2
Tractor Mounted Sweeper	2
Paint Machine	2
RRR Trailer	3
1500-Gallon Water Truck	3
Dolly Converter (8-ton)	3
Basic RRR Equipment support Kit	1
Basic RRR Airfield Lighting Kit	1
AM-2 Airfield Lighting Kit	6
AM-2 Support Kit	2
Folded Fiberglass Mat FOD Cover Kit (Kit-A)	1
Folded Fiberglass Mat FOD Cover Kit (Kit-B)	2
Spall Repair Kit	4
Minimum Operating Strip Masking System (MOSMS)	1

Table 4 Equipment Used by the RRR Team

Basic RRR Set

The basic set was developed by the Air Force to provide a primary bomb damage repair capability for air bases. When originally designed, the equipment in this set supported the repair of three 15 m bomb craters with AM-2 matting within a 4-hour period. The R-1 set also supports the folded fiberglass mat method using the same criterion. The basic RRR set is currently in place at most high-threat main operating bases. The components of the current vehicle and equipment sets are the area to concentrate and develop a vehicle, which could deploy the mat with minimal requirements.

Summary

The detailed study of earthquake road damages, RRR concepts and its process, and Crater Profile Measurement concepts were performed which helped to develop an idea of how to tackle earthquake damages on highways. The crater profile measurement needs manual inspection, which makes it tedious. Automation would enhance the measurement process. A dynamic measurement process would be an ideal solution. Reduction of intensive labor and equipment also become a major concern to make this repair efficient. During the study it was found that the FOD cover plays an important role in the RRR process. The later chapters deal with the structural analysis of the FOD mats. Since earthquake damage does not normally leave any upheaval, an ideal solution would be to design a mat structure that acts as a temporary pavement over the unfilled cracks and fissures.

Chapter 3. Damage and Repair Specifications

In order to better understand what kinds or repairs are necessary to open damaged roads to traffic, this chapter examines more closely the types of damage likely to be encountered after an earthquake. Also discussed are the probable numbers of repairs based on road closure predictions for different fault rupture scenarios. Finally, some information about the repair structure target specifications will be discussed.

Damage Types

The most important types of damage to a road repair study are those that disrupt the road's driving surface. In the previous chapter, the types or road closures were broken into those with direct causes and those with indirect causes. Two direct causes of closures, surface faulting and liquefaction, have the most significance to road surface damage. The nature of earthquakes and the damage they produce is that they are very unpredictable, but there are some formulas, covered in the following two sections, that can be used to provide estimates of the damage size.

Surface Faulting

In their earthquake modeling, ABAG uses formulas that relate earthquake moment magnitude to the lateral and vertical surface faulting displacements of strike-slip faults (Perkins et al, *Riding out* 17). The moment magnitude of a fault rupture based on the fault length is represented as

$$MM = 5.16 + [1.12 \log (L)] \tag{3.1}$$

where MM denotes the Moment Magnitude of the fault rupture, and L denotes the Fault Length in km.

The average horizontal displacements and vertical offsets based on fault rupture moment magnitude are given as

$$\log (AH) = -6.32 + (0.9\ MM) \tag{3.2}$$

$$AV = 1/3\ (AH) \tag{3.3}$$

where AH is the Average Horizontal Displacement in m and AV is the Average Vertical Offset, also in m.

The actual average horizontal displacement, Eqn. (3.2), can range from 1/2 to 2 times the calculated value. Strike-slip faults have average vertical offsets that range from zero vertical offset up to 1/3 of the average horizontal displacement. The maximum horizontal displacement and maximum vertical offset based on fault rupture magnitude are expressed as

$$\log (MH) = -7.03 + (1.03\ MM) \tag{3.4}$$

$$MH = 2\ (AH) \tag{3.5}$$

$$MV = 1/3\ (MH) \tag{3.6}$$

where MH representing the Maximum Horizontal Displacement in m and MV denoting the Maximum Vertical Offset, also in m.

There are two equations for the maximum horizontal displacement, providing lower and upper range values. The lower value is calculated using Eqn (4), and as with the average horizontal displacement, the actual value can be 1/2 to 2 times the calculated value. The upper range value is simply double the calculated average horizontal displacement, Eqn (5), a value observed over short sections in actual fault rupture. The maximum vertical offset is 1/3 of the maximum horizontal displacement calculated with Eqn (4).

According to the equations, a 44 km [27.3 mile] strike-slip fault will produce a 7.0 moment magnitude rupture, resulting in an average horizontal displacement of 1.0 m [3.1 ft], but actual ruptures can have horizontal displacements that range from to 1/2 to 2 times this value. The calculated range for the average vertical offset is from zero to 1/3 of the horizontal displacement, or in this case 0.3 m [1.0 ft]. The calculated maximum horizontal displacement ranges from 1.5 m [5.0 ft] to 1.9 m [6.3 ft]. The maximum vertical offset is taken as 1/3 of the lower range maximum horizontal displacement value, 0.5 m [1.7 ft] in this case.

Observations from the Landers Earthquake (a strike-slip fault) in 1992 lend more insight into surface faulting. The Landers Earthquake matched the equations for maximum horizontal and vertical offsets quite nicely. The 80 km [50 mile] fault had lateral offsets of 3 m [9.8 ft] to 4 m [13.1 ft] with areas of maximum 1 m [3.3 ft] vertical shift. This earthquake also demonstrated that even strike-slip faults can cause grabens (chasms) and that faulting in hilly topography is more likely to have vertical offsets, or apparent vertical offsets. It was observed that areas of localized compression tended to buckle road surface materials such as concrete and sometimes asphalt. Also noted was that after the earthquake, residents in the area were usually willing to drive over road disruptions that either the CHP or Caltrans did not view as appropriate for through traffic (Perkins et al, *Riding out* 18-19).

Having an idea of what size damages might be expected from ruptures along the faults in California provides an estimate range for repair sizes. Typically the faults in the Bay Area have lengths that correspond to earthquake scenarios with magnitudes ranging from 6.5 for a rupture along the West Napa Fault to 7.9 for a rupture of the entire Bay Area San Andrea Fault. Using the equations presented above, the average vertical offsets range from 0.1 m [0.3 ft] for the magnitude 6.5 earthquake to 2.1 m [6.9 ft] for the magnitude 7.9 earthquake. One thing to keep in mind is that continued fault creep after the earthquake may adversely affect a repair structure.

Liquefaction

Liquefaction can damage runways and roads by causing lateral spreads, ground oscillations, and differential settlements. A lateral spread is similar to a landslide but it occurs on slopes of less than 3 degrees. The layer of ground at the surface is carried over the liquefied material underneath, usually toward a river channel or other bank, moving about 30% of the thickness of the saturated loose material. This causes fissures and scarps at the surface layer. Ground oscillation failures occur because of the decoupling between the top layer and the loose material beneath it. This allows the top layer to move back and forth, and up and down in a different way than the surrounding material leading to large cracks. Differential settlements happen when the soil compacts and settles in a non-uniform way after the shaking has stopped. Settlement is usually about 1% - 5% of the thickness of the material that liquefies, but can be up to 10% in very loose sands. Liquefied layers that are not of a uniform thickness are particularly prone to differential settlement; this is usually found in fills done at different times (Perkins, *Real Dirt on Liquefaction* 2-3).

Liquefaction damage was observed at the Oakland International Airport after the Loma Prieta Earthquake in 1989. About 910 m [3,000 ft] of the 3050 m [10,000 ft] main runway, built on hydraulic fill, experienced cracking damage due to liquefaction. Cracks 0.3 m [1 ft] wide and 0.3 m [1 ft] deep were observed on the runway. On adjacent unpaved land, spreading caused cracks up to 0.9 m [3 ft] wide and in some places were observed to be 3.0 m [10 ft] deep. The runway also had several vertical offsets with some as high as 0.3 m [1 ft] (Perkins et al, *Riding out* 68; Perkins, *Real Dirt on Liquefaction* 14). A question associated with repairing liquefaction damage is whether or not the stability of the surrounding ground is sufficient to support a repair structure.

Repairable Damage

Information regarding the number of expected repairs might be a factor used in determining the number of repair structures to carry and the speed at which the repairs should take place. Road closures are the starting point to estimating the number of expected repairs for Bar Area earthquake scenarios. According to the ABAG predictions, road closures for earthquakes along bay area faults will range from less than 100 to over 1700 closures. These high numbers include closure caused by both direct and indirect causes. More importantly the predictions for closures due to the combined effects of surface faulting and liquefaction, the types of damage that mostly affect the road driving surface, range from 21 to 611 and average 160.

During the Northridge and Loma Prieta earthquakes about 40% of the closures due to direct causes were impassible, but only 15% of liquefaction closures were impassible and none of the closures were due to surface faulting. So taking the worst-case with 611 closures, assuming 40% of the 520 surface faulting closures and 15% of the 91 liquefaction closures will be impassible, the predicted number of impassible closures due to faulting and liquefaction is 222. Of these 222 impassible roads, only a percentage (say 80%) will be repairable, in some cases the damage may be too great, and of those damaged sections, only a percentage (say 75%) will be along critical transportation corridors or in areas where a detour is an undesirable option. This leaves 133 impassible roads with damage in the scope of the machines repair abilities and which area a priority for opening.

Again, the above rough calculations were for the worst-case scenario, a rupture of the Northern and Southern Hayward Faults. Running through the same calculations for all of the 18 Bay Area earthquake scenarios and averaging the results returns an estimated mean 32 impassible, repairable, critical closures. The following table contains a summary of these calculations for the rest of the fault rupture scenarios.

For the average case, two vehicles in the Bay Area could easily handle all of the 33 repairs. In the upper end case with 133 repairs, if two vehicles split the work that comes out to just less than 70 repairs per vehicle. If the repair structures used for the repairs were 2.4x3.7 m [8x12 ft] composite plates weighing estimated 600 pounds each, then a vehicle with 70 plates would be hauling about 42,000 pounds. Realistically not all 70 repairs would need to be made in a row so restocking of plates or repair structures would be an option. A vehicle might only have to carry somewhere from 3 to 15 repair structures, depending on the type of structure used. Also structures of different sizes might be carried for repairing damaged sections of varying length, width, height, and configuration.

Repairable Closure Calculation Summary

COUNTY	Total No. Road Closures	No. Due to Faulting	No. Due to Liquef.	Faulting 40% impass.	Liquef. 15% impass.	Combined	80% Repairable	75% Critical
San Andreas – S.C. Mts.	154	25	7	10	1	11	9	7
S. A. – Peninsula - G Gate	866	163	40	65	6	71	57	43
S. A. - N. Golden Gate	581	29	29	12	4	16	13	10
S. A. - Entire Bay Area	1332	217	73	87	11	98	78	59
No. San Gregorio	401	58	22	23	3	27	21	16
Southern Hayward	1138	346	66	138	10	148	119	89
Northern Hayward	667	174	29	70	4	74	59	44
N + S Hayward	1734	520	91	208	14	222	177	133
Rodgers Creek	402	82	32	33	5	38	30	23
Rodgers Cr - N. Hayward	1084	256	58	102	9	111	89	67
Southern Maacama	74	22	2	9	0	9	7	5
West Napa	159	45	8	18	1	19	15	12
Concord-Green Valley	386	102	27	41	4	45	36	27
Northern Calaveras	363	84	41	34	6	40	32	24
Central Calaveras	210	27	15	11	2	13	10	8
Mt. Diablo Thrust	228	0	21	0	3	3	3	2
Greenville	138	25	9	10	1	11	9	7
Monte Vista Thrust	326	111	16	44	2	47	37	28

Table 5 Repairable Closure Calculation Summary

Repair Specifications

The next two sections discuss some initial physical specifications of the repair structure, such as loading and slope. The maximum slope is useful in providing a physical boundary to the repair structure design. Depending on the length of ramp or plate used a maximum slope will proved a maximum vertical clearance.

Vehicle Axle Weight Info

The vehicle axle weight limits in the California Vehicle Code are based on the Federal Bridge Gross Weight Formula, which is used to calculate what acceptable axle weights are for various axle groupings and spacings. The vehicle gross weight limit is 360 kN [80,000 pounds], while the axle weight limit is 89 kN [20,000 pounds] for a single axle and 150 kN [34,000 pounds] for tandem axles. These are given as an upper weight that the repair structure might be required to hold. A minimum weight the repair structure might be required to support comes from what are probably the most common cars on the streets, Toyota Corolla's and Honda Civic. These cars have gross unloaded weights of about 11 kN [2600 pounds] and a 60/40 axle weight distribution, about number 6.7 kN [1500 pounds] on the front and 4.4 kN [1000 pounds] on the rear axle. Important vehicles that will very likely need to cross over a repair will include Police, Fire, Medical, Maintenance (Water, Gas, Electric, Sewer), and Food and Supply Delivery trucks and vehicles. The repair structure will need to support loads and provide a suitable driving surface for a great majority of these types of vehicles.

Information About Slope

The slopes of driveways were used to get an idea of the maximum slope it is practical to have a ramp or plate inclined at. Typical driveways are limited to slopes of 15% to 20% or angles from 8.5° to 11°. For a 2.4 m [8 ft] surface, a 20% slope corresponds to a rise of about 0.48 m [1.6 ft] on a flat road. Trying to maintain an overall plate slope of 20% of roads with a slope will reduce the repairable vertical offset. Just for reference the steepest street in San Francisco has a slope of 31.5%, an angle of 17.5°. Obviously it would not be possible to maintain a slope of 20% on a street with a 31.5% slope, but these extremely steep streets do not generally support major traffic and if damaged, they will not be a high priority for immediate repair. The steepest highway sections run at about a 7% slope or about 4°, about half of the maximum ramp or plate inclination.

Specification Summary

The information on the size estimates for damage from surface faulting and liquefaction are based on fault length and earthquake magnitude for surface faulting and fill depth for liquefaction. The estimations of the number of repairable closures are based on ABAG's predictions for future road closures for different fault rupture scenarios. The information for the repair structure slope was gathered through research on typical driveways, streets and highways. One thing to note is that a magnitude 7.0 fault rupture will produce estimated vertical offsets averaging 0.3 m [1ft], within the range of vertical clearance of a 2.4 m [8 ft] ramp with a slope of less than 20%. The following table summarizes the information presented in this chapter.

Summary Tables

Surface Damage	Strike-Slip Faults		Liquefaction	
	ABAG Modeling Eqns. Mag. 7 rupture	Landers Earthquake example	General Observations % of fill Depth	Loma Prieta and OAK example, In Pavement
Ave Horizontal	1.0 m	3 m - 4 m	30%	0.3 m wide 0.3 m deep

Ave Vertical	0.3 m	1 m	1% - 5%	up to 0.3 m vertical
Max Horizontal	1.5 m	Apparent Vertical		Adj soil 0.9 m wide
Max Vertical	0.5 m	Concrete Buckle	10%	3.0 m deep

Slope	**Typical limits for driveway slopes, % slope**	**Equivalent degrees**	**Vertical Rise of 8 ft ramp on flat ground, ft**
Unpaved	12	6.8	0.95
Paved Lower Limit	15	8.5	1.19
Paved Upper Limit	20	11.3	1.57
Typical steepest highway section	7	4.0	
For comparison, the steepest road in SF	31.5	17.5	

Number of Repairs

Closure estimates	**ABAG Total Closure**	**Repairable Closures**
Max	1734	133
Min	74	2
Average	569	33

Vehicle Weights	**Gross Vehicle, lb**	**Single Axle. lb**	**Dual Axle, lb**
Federal Bridge Formula Used to by CVC to determine safe weight limits	80000	20000	34000
Popular Cars Toyota Corola, Honda Civic	2550		
Critical Vehicles - Fire Vehilcle	~ 35000		

Table 6 Summary Tables for Chapter 3: Damage and Repair Specifications

Chapter 4. Design Concept Development

With a repair concept in mind (Road Cover) and the nature of the road repairs defined, the focus can now be brought upon the development of conceptual designs. The goal of this chapter is to clearly explain the process used in generating and selecting rapid road repair design concepts.

Rapid Road Repair Goals

The conceptual design process will begin with a discussion of the intended use and repair procedure of the equipment and repair vehicle. This discussion will help identify the main functions necessary to satisfactorily complete the repairs. Additionally, it will lead to the development of functional groups, useful in guiding the idea generation.

Design Considerations

One of the major aspects of the rapid repair concept is fast response time. This is accomplished with close proximity to the damage site and by easily transportable machinery and equipment. The idea is to have the equipment stationed at several locations around the state, ready in the event of an emergency or earthquake. Since this equipment is intended for use during emergency situations, it could spend the majority of its life in equipment yards. This point brings up a few design goals. The repair machinery and equipment must be mobile, it must open damaged roads to traffic (especially maintenance and emergency vehicles), and it must be reliable and relatively unaffected by long periods of inactivity.

Because of the possible extended downtime a dedicated earthquake emergency vehicle would experience, combining the repair equipment with an existing truck or machine would reduce the amount of stored equipment. For example, the repair machine or equipment could come as some sort of add-on or attachment, or as a trailer rather than a much larger self-contained unit capable of transporting itself. In the event of an earthquake, the machine would be loaded or hitched and then driven or towed to the section of damaged road. If the repair machinery were going to be an entirely new standalone piece of equipment, ideally it would be capable of accomplishing other tasks to broaden its range of application.

The general repair concept is for a system that deploys a structure of some sort to cover damaged sections of road. The structure used for the repair can be anything from a simple road cover plate to a more complex truss bridge structure. The important part is that it can support the weight of the vehicles using it and is of a size that can accommodate the width of the vehicles driving over it.

Something to consider is the weight of the repair structure, e.g., 2.4 x 3.7 m [8 x 12 ft] composite plates would weigh an estimated 2,700 N [600 lbs]. Other types of repair structures might weight less for smaller sizes or more for increasingly complex structures. Relatively minor road damage may only require a single repair structure or, if the structure is scalable, its minimum form. If the damage is more severe, more structures and supports may be necessary to completely cover the damage and stabilize the repair structures.

Repair Use Discussion

To accomplish the repairs, the repair structures first need to be loaded and transported to the site of the road damage. After all of the machinery and equipment has arrived at the road section to be repaired, the next steps are removing the repair structures from their stowed location, performing any assembly if necessary, and positioning them where needed to cover the damage. Depending on how the repair structures and equipment arrive at the repair site, some maneuvering of the vehicle or vehicles may need to take place. Once completed, the positioning and alignment of the structures can begin.

The next step concerns the alignment of the repair structure. Depending on the type of repair structure, it may have a permanent support structure or supports that can be attached to it. Additionally the supports or support structure may have some range of height adjustability. These supports will allow the repair structure to adapt to different types of road damage, from vertical offsets to uneven or canted surfaces. In addition to positioning and orientating the structures, one needs to think about its height and alignment with the road surface and any other structures.

Adjustable supports could be used to raise or lower the repair structure into position. If the supports are not used for positioning, then the alignment of the structure will need to be achieved by some other method, say a crane or temporary jacks. Nonpermanent supports might be attached to the structure before or after it has been removed from storage, and either before or after its position has been set. Ideally an option would exist so the adjustments made to plate alignment and height could be done by remote control or some automated fashion rather than only manually.

Once the structure has been placed, it needs to be strong and stable enough to accommodate maintenance and emergency vehicle traffic. After the structure has been set, its supports may need to be adjusted to account for continued fault creep after an earthquake, or after supporting heavy vehicles, as some settling might occur. The following table contains a summary of the necessary steps that occur during a repair.

Main Functions

1	Everything must be packed up and loaded, if it is not stored that way
2	All equipment and repair materials must be transported to the site of the damage
3	At the repair location the machinery and equipment must be unpacked and readied
4	The repair material must be removed from its stowed position
5	If necessary the repair material will be assembled into a structure
6	The repair structure must be aligned and put in place
7	If necessary the height of the structure will be adjusted

Table 7 Main Functions of Repair Structure

Functional Groups

Based on the above list of necessary repair steps, the design of the Road Cover concept can be broken into two categories, the repair structure and the delivery method. The repair structure category includes the design of what is actually going to be used to cover the damaged road. The delivery method category includes the design and planning of how everything gets from the Caltrans equipment yard to its final location at the repair site, including the positioning of the repair structure.

The design of the repair structure has many issues associated with it: such as the simplicity of the structure, the adjustability of the supports, whether or not multiple structure sizes are necessary. The repair structure must provide a driving surface for vehicles that covers or spans the damaged road. More in depth categorization of the repair structure includes the actual surface the vehicle's tires will contact, the points of contact with the existing road and damaged surface, and the support structure between the road contact points and the driving surface.

The repair structure will also need some adjustability to deal with different types and sizes of repairs and road damage. Some questions that will need to be answered are how the adjustability will be implemented, when it will occur during the deployment and where on the structure it will take place. Ideally the leveling and alignment of the driving surface would be designed so it could be performed automatically or remotely. Somewhat complicating the design of the structure is the fact that some of the functions can, should, or possibly need to be performed by or in conjunction with the delivery method. Specifically, the functions and issues having to do with height positioning and alignment might be better integrated with the delivery method.

The delivery method category has two main subdivisions, the transportation of the repair structure and its deployment. The transportation subdivision includes the stowage of the repair structures during transport and the method of transportation to the repair site. The deployment subdivision includes the operations associated with moving the repair structure from its stowed transportation position to its final location. The interface between the repair structure and the deployment method is one that requires attention to ensure easy placement and alignment. Following is a graphical representation of the functional groups.

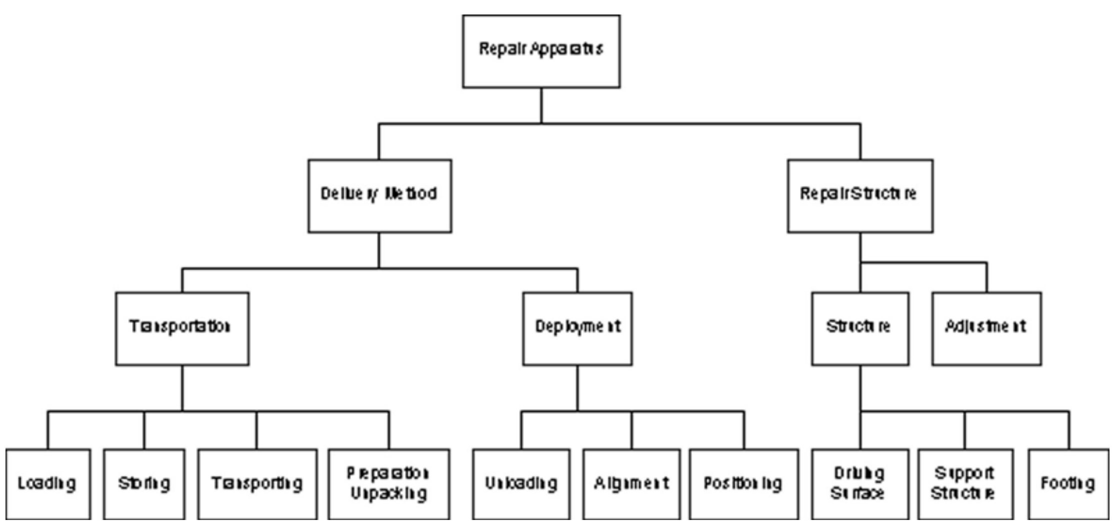


Figure 10 Functional Grouping of Repair Structure and Deployment Method

Idea Generation

The following sections discuss the process used to generate rapid road repair ideas and how complete conceptual designs were selected. In the beginning of the design process, a morphological chart based on the functional groupings was created to help organize the idea generation process. The immense size and number of possible design combinations of the original morphological chart required that some modifying be done to the chart in order to obtain a manageable set of design possibilities. Since the design of the repair structure will dictate the design of the delivery method, a reduced morphological chart was used that focused on the repair structure design. By eliminating less promising designs, the repair structure concepts were reduced to a smaller group that could then be compared using a selection matrix. The remaining repair structure concepts were then paired with different deployment methods and compared on several earthquake road damage scenarios. The earthquake road damage scenarios were selected to represent a range of repair difficulty in order to see which repair structure and deployment combinations would perform the best under a broad range of conditions.

Morphological Chart

A morphological chart was used as an aid in the design process, with eleven chart categories matching the functional groups and divided the same way. Design ideas that had come up during the earlier research were broken into headings with short names that could be placed under one of the morphological chart categories or topics. Putting all of the existing design ideas into the chart quickly showed which areas of the complete conceptual design needed more thought. Design ideas were generated to fill in the slimmer areas and thicken out the rest of the categories. During the idea generation, no judgment was made as to whether or not the category ideas would fit with the overall concept. For instance, when coming up with ideas for the repair structure Driving Surface category, the emphasis was placed simply on coming up with different driving surface ideas, with little attention being paid to whether or not the ideas made sense in the context of the overall rapid repair design. The elimination of ideas that did not logically fit with the entire design would come later.

Between four to six ideas were generated and listed in the morphological chart for each category. With four to six ideas per category and eleven categories, this chart could in theory have 64.8 million possible design combinations, see the following table for the complete morphological chart. Obviously this is far too large of a number of design concepts to be considered on an individual basis. In reality though, many of the combinations only work with certain ideas while other combinations do not make logical sense. Closer inspection of the chart reveals that some of the ideas don’t need to be considered individually. In a few cases they are so similar to other ideas that they can be combined, and yet in some other cases whole morphological chart categories can be deleted for their lack of bearing on the design architecture. Taking into account the fact that the design of the repair structure will have a large part in determining the delivery method (the transportation and deployment of the repair structure), a reduced chart is created featuring only the repair structure.

The reduced morphological chart, besides only featuring the categories relevant to the repair structure, Driving Surface, Support and Adjustment, has some other changes. The Footing category has been eliminated because of its lack of importance to the overall design. There are also some minor changes to the idea headings, notably the addition of the None/Integrated Support idea. This reduced chart has 180 possible repair structure design combinations.

Complete Morphological Chart

			1	2	3	4	5	6
Repair Structure	Structure	Driving Surface	Wheel Tracks	Planks	Plate	Bridge/Ladder	Mat	
		Support	Trailer	Rail/Girder	Post/Pillar	Truss/Trestle	Epoxy Pier	
		Footing	Integrated w/ support	Continuous Track	Foot Plates	Locking Wheels	Matting	
	Adjustment		Fixed	Air Bags	Screw Jacks SpiraLift	Ratchet Jack	Scissor Jack	Pistons (hydraulic)
Delivery Method	Transportation	Loading	Unit Hitched	Stored Ready	Part Bundles Loaded	On Board Crane	Lift Platform	Fork Lift
		Storing	Stacking	Horizontal Rack	Vertical Rack	Lean On End		
		Transporting	Towed Trailer	Specialized Vehicle	Truck Bed	Truck and Trailer	Multiple Vehicles	
		Preparation	Un-Hitch	Assembly	Maneuvering	Readying Equipment	Scouting Location	
	Deployment	Unloading	By Hand	Lift Gate	Boom Arm Center/Edge	Wall Mover and Edge Clamp	False Bottom	Fork Arms
		Positioning	Pivoting Deck	Track	By Vehicle	Crane	Dolly	Tip Over Edge
		Alignment	By Supports	Additional Temporary Jacks	Crane	Lift Gate		

Table 8 Complete Morphological Chart

Reduced Morphological Chart

			1	2	3	4	5	6
Repair Structure	Structure	Driving Surface	Wheel Tracks	Planks	Plate	Bridge/Ladder	Mat	
		Support	Trailer	Rail/Girder	Post/Pillar	Truss/Trestle	Epoxy Pier	None/Integrated
	Adjustment		Fixed/External	Air Bags	Screw Jack SpiraLift	Ratchet Jack	Scissor Jack	Pistons (hydraulic)

Table 9 Reduced Morphological Chart

Idea Descriptions

The following sections contain descriptions of the ideas within each of the three idea categories, Driving Surface, Support Structure, and Adjustment, in the reduced morphological chart.

Driving Surface:

As can be seen in the reduced morphological chart, there are five different Driving Surfaces, named in the order listed in the chart, Wheel Track, Planks, Plate, Bridge, and Mat. The Wheel Track driving surface idea is self-explanatory. It consists of two parallel driving surfaces wide enough to handle dual wheel sets and spaced at a distance apart that will accommodate most vehicles. The driving surfaces may either be rigid enough to support the vehicle weights on their own or they may have an accompanying frame. One of the benefits of the Wheel Track idea is that is could either be part of a structure that stores small and is assembled at the repair site or it could be a larger permanent assembly.

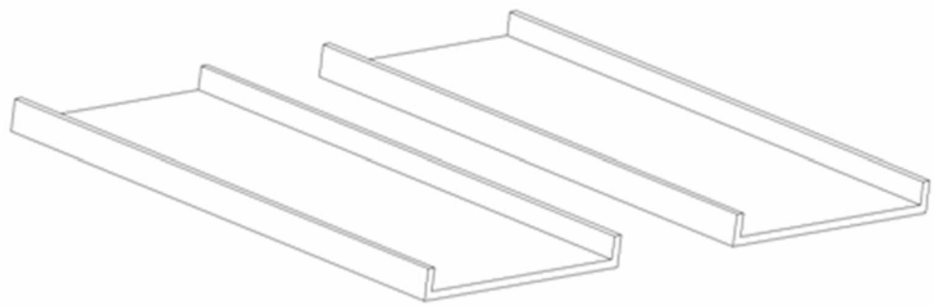


Figure 11 Wheel Track Driving Surface

The driving surface Plank idea centers around using a frame that decking or planks are attached to. A basic incarnation would have two rails or beams running the direction of travel under the load path of the vehicle's wheels, with planks running over and across the beams. This idea would also easily store, but would likely have a bit of assembly time associated with it. The rails with planks running across configuration could also be set up skewed, very useful in covering damage between two uneven road surfaces.

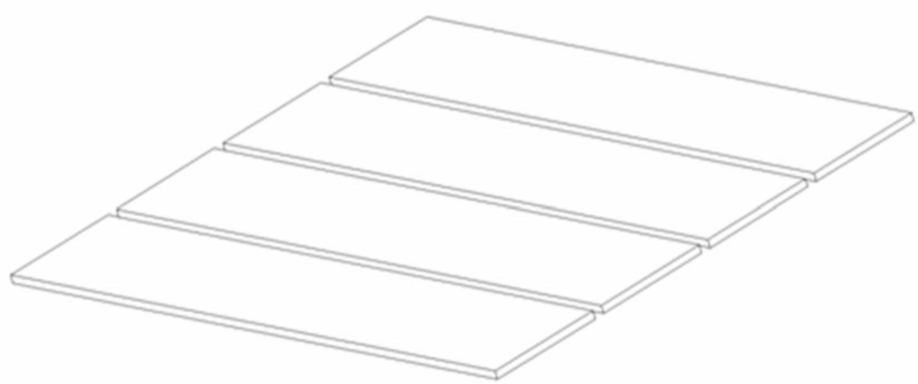


Figure 12 Plank Driving Surface

The Plate idea is simply a rectangular plate, possibly made of composites that could have varying sizes and thickness for different applications. One probable plate size would be the width of a traffic lane, with a shorter traffic direction length, 2.4 x 3.7 m [8 x 12 ft]. Depending of the type of support structure used, the plate would have reinforced mounting areas for the supports. A flat plate structure would store and transport fairly easily, but might be a bit unwieldy during deployment. The simplicity of the plate would make it easy to scale to different repairs.

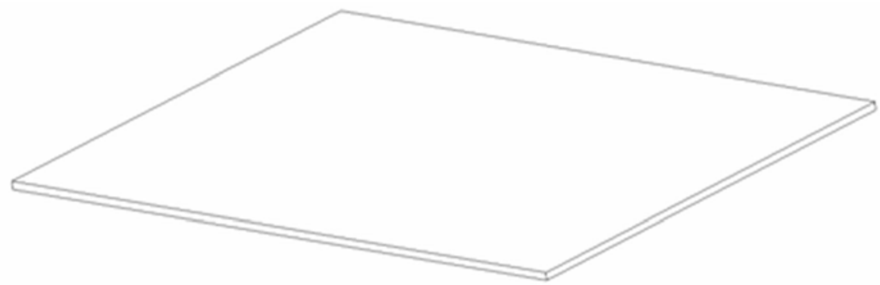


Figure 13 Plate Driving Surface

The Bridge idea is to have a driving surface that is arched or raised in the middle with an accompanying support structure underneath. This would involve a fairly large structure, similar in concept to military mechanical bridges that have one or two hinges and fold for storage. Upsides to this idea are its possible large spanning and weight carrying capabilities. The downsides are that the bridge may in many cases be far more than needed for the smaller repairs and could be quite cumbersome to deploy and transport. An inability to store small might limit the transport to a single unit, reducing its repair capabilities.

Figure 14 Bridge Driving Surface

The Mat driving surface idea is for a semi-rigid mat that can be rolled up for storage and rolled out to cover loose or unstable ground. To completely bridge over damaged road sections, the mat could be used in conjunction with a frame structure, adding the strength and rigidity necessary in order for the mat in to support the loads of passing vehicle.

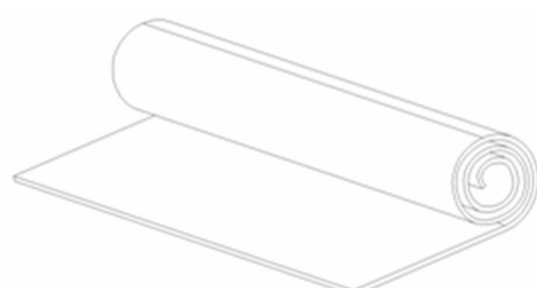


Figure 15 Mat Driving Surface

Support Structure:

In addition to the Driving Surface ideas, the morphological chart in *Table 8 Complete Morphological Chart* also lists six Support Structure ideas, Trailer, Rail/Girder, Post/Pillar, Epoxy Pier, Truss/Trestle, and None/Integrated. The idea behind the Trailer support structure is that the driving surface will be supported by a trailer structure, which will allow the repair unit to be towed into place. Once at the site of the road repair the trailer could be maneuvered into place, unhitched, and additional supports could be lowered to secure the trailer structure and the repair would be done. While the trailer idea seems very simple to use and answers many of the transportation and deployment questions, it has some drawbacks. One drawback is that only one unit (or possibly a few if they are stacked on top or each other or trained together) may be transported at a time. Also because it is a trailer, it may have difficulty being properly deployed because the road will of course be damaged, preventing the trailer from being driven right up to actual repair.

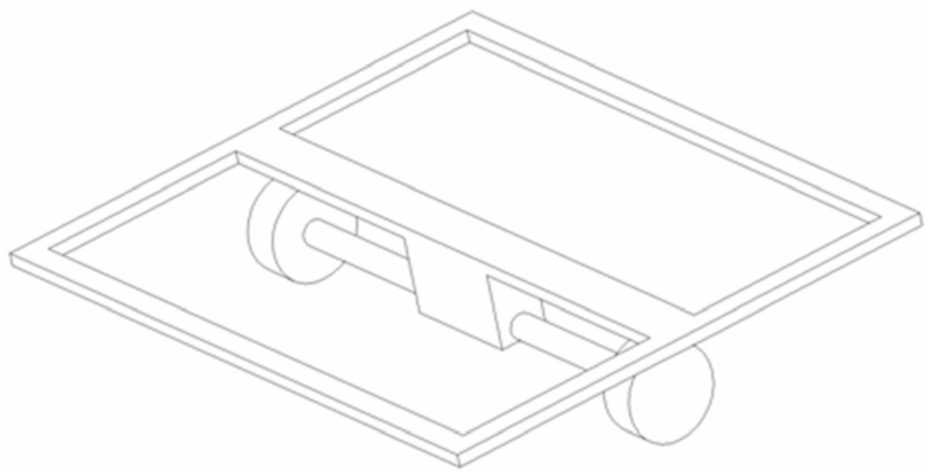


Figure 16 Trailer Support Structure

The Rail/Girder support idea is pretty simple; box or I-beam rails will provide the structural support for the driving surface. The rails might permanently be a part of the driving surface or the two might attach during the deployment of the repair structure at the damage site. Having rails that are telescoping would afford the system a good deal of adaptability. Depending on the repair scenario, a rail/girder support structure might need some additional type of vertical support when it is not ideal to simply have the driving surface resting on the ground.

The Post/Pillar support structure could have several different embodiments but the basic idea is for vertical posts that support and stabilize the driving surface. This could be implemented with a driving surface by having these posts permanently fixed to the driving surface or they could have the option of attaching to it at several places depending on the nature of the repair. Posts or pillars of different heights and sizes and possibly with length adjustability would increase the repair options. An adjustable post type support could be operated in several ways including telescoping pneumatic or hydraulic pistons, screw jacks and ratcheting lifts. The biggest issues with the Post/Pillar ideas have to do with the nature of the attachment point and implementing the adjustability. It would be possible to have non-adjustable permanently fixed supports on a driving surface, but it may limit the repair structures ability to handle unpredictable and varying repair condition as well as reduce its ease of transport.

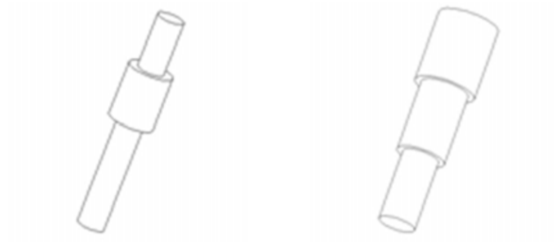


Figure 17 Post/Pillar Vertical Support

The Truss/Trestle support idea involves using a truss frame to support the driving surface and trestle structures to provide, if necessary, height for repair structure clearance. A truss support frame does not necessarily need to be permanently attached to the driving surface and could also be designed to disassemble for storage. A truss support frame could have the advantage of a lighter overall structure. Besides being a more complex structure, the truss/trestle idea may not scale and adapt to different repair situations and sizes.

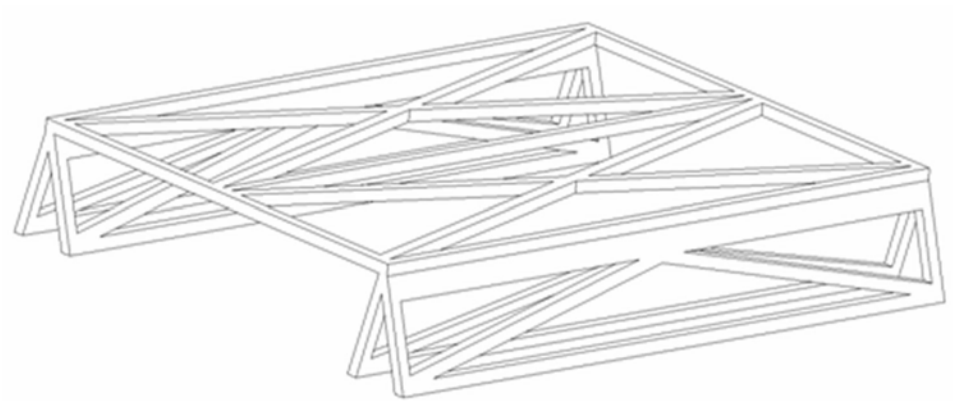


Figure 18 Truss Support Structure

The Epoxy Pier support structure has basically the same embodiment as the post/pillar idea, the difference is in its deployment. The idea is that once the desired height and position of the driving surface had been established, a quick hardening epoxy substance would be used to form a support pier underneath the driving surface, maintaining the structures desired height. A major benefit of the idea is that piers of different heights could be quickly and easily made at the repair site, as they were needed. Once the pier had hardened though, making height adjustments would be difficult, probably requiring that the old pier be removed and a new one created.

The last support idea on the list, None/Integrated, is included on the morphological chart simply to indicate that the driving surface may either not need a support structure or as in the case of the bridge driving surface, the support structure could be part of the driving surface.

Adjustment:

The last row in the morphological chart lists six adjustment methods ideas, Fixed/External, Air Bags, Screw Jacks/Spiralift, Ratcheting Jack, Scissor Jacks and Hydraulic/Pneumatic Pistons. The first adjustment idea, Fixed/External, describes a system where either the repair structure has no vertical height adjustment or where the adjustment is done externally by the structure placement mechanism or using temporary lifts while a fixed height support is put in place.

Much as the name implies, the Air Bags adjustment idea relies on using a system similar to the suspension of large trucks for height adjustability. A compressor or air tank on the delivery vehicle could control the inflatable air bags, which would be used in conjunction with the support structure to provide the necessary height adjustment.

The Screw Jacks/Spiralift adjustment idea is based on a typical screw jack for height adjustment. Depending on the configuration used, the screw jack could be mounted under the driving surface and provide a small amount of adjustment (on the order of 10 cm [3.9 in]) or a longer threaded jack could be mounted on the side of the driving surface, providing all of the necessary adjustment. A Spiralift is a mechanical actuator that extends itself by continuously building onto itself with interlocking coils. A Spiralift has the advantage of having a short storage space for the height that it can extend. The screw jack or Spiralift could be motor or hand actuated.

Another adjustment idea is to use a Ratchet Jack, which would have a similar embodiment to a screw jack, only that it would be actuated differently. A downside to both the screw jack and ratchet jack is that take up quite a bit of space for the amount of lift they provide.

Although Scissor Jacks have a different appearance than Screw or Ratchet Jacks, as an adjustment method they would be used in a very similar way. Scissor Jacks have an advantage of being highly collapsible, allowing them to take up very little space if permanently attached to a Support Structure.

The last adjustment idea on the morphological chart is to use Hydraulic/Pneumatic Pistons. These pistons could serve as post type supports with a large range of adjustment or they could work in conjunction with the support structure providing a smaller amount of adjustment. A hydraulic actuated piston would need a pump either on the structure or on the deployment vehicle and a pneumatic piston would need an air source. A configuration that would avoid this would be to have telescoping pistons nested inside of each other, with an air extension spring controlled with a hydraulic valve.

The Structure Sketches

To get a better grasp of the compatibility between the ideas, the Driving Surface ideas were paired with the Support ideas and the Support ideas were paired with the Adjustment ideas. Sketching out and thinking through the 30 combinations of the Driving Surface ideas with the Support ideas led to some observations. Immediately it was clear that some of the combinations either did not make sense together or were nearly impossible to imagine. What was noticed about the pairing of the Support ideas with the Adjustment ideas was that nearly all of the combinations were compatible, meaning that any type of support structure could be made to include any type of adjustment method. This was true for all of the combinations except of course for the Epoxy Pier Support idea which would have to be externally adjusted before the pier height was set and the None/Integrated Support idea which also meant the driving surface would have a fixed height or would be externally adjusted. Because of this, the only real choices that would affect the overall repair structure architecture are the Driving Surface and the Support Structure.

The following paragraphs contain descriptions of the various Driving Surface and Support Structure combinations as well as illustrations. The following paragraphs describe some of the important points and notes that were made clear after sketching out drawings of the various driving surface and support structure combinations. Some initial judgments of the combinations are also presented. The paragraphs are organized in a way similar to how the sketches were done, focusing on one single driving surface at a time and matching it with each of the support structures.

Wheel Track:

The Wheel Track driving surface and its combinations with the six types of support structures are described now. The first combination is the Wheel Track and the Trailer. This combination seems to make sense allowing the driving surface to be towed to the repair location, requiring little setup. This might also be a drawback because getting close to a damaged road section might be difficult or impossible with the wheeled trailer. Also the size might make transportation of more than one unit at time difficult, requiring additional trailers to be stacked together or hitched in a train like fashion.

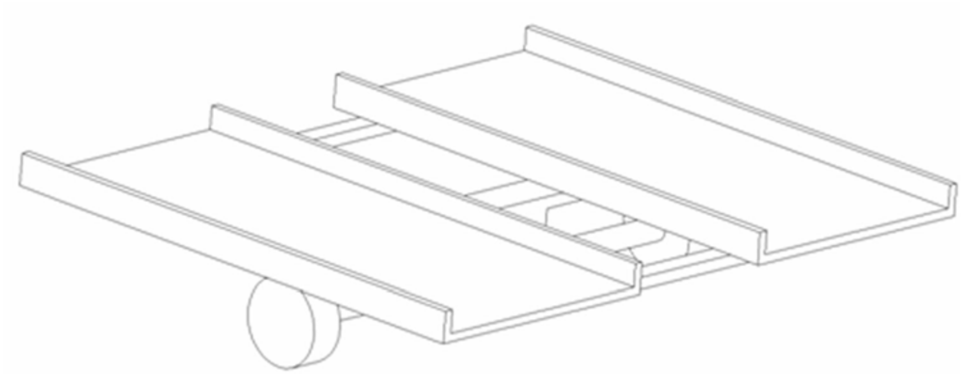


Figure 19 Wheel Track and Trailer Combination

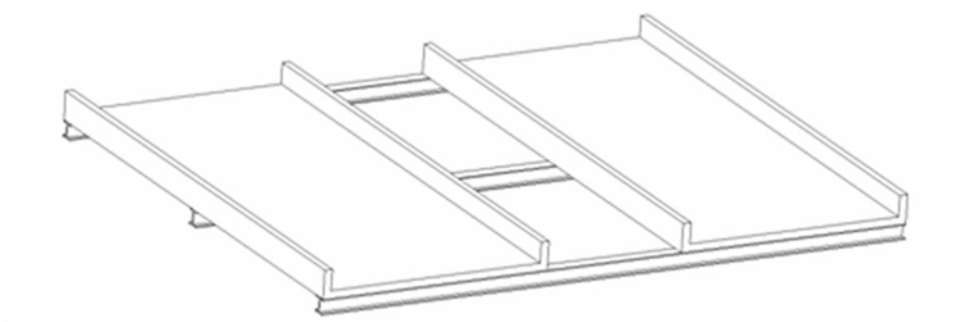


Figure 20 Wheel Track and Rail Combination

The second combination, Wheel Track and Rail/Girder only makes sense if the rails are running across the structure, perpendicular to the wheel track and below the driving surface. A configuration like this might allow the width of the wheel tracks to be adjusted, having them slide together for storage and apart during deployment. But this system alone lacks any heightening capabilities, and that is why it makes more sense when employed with the third and fourth combinations, the Post/Pillar and Epoxy Pier. Having a vertical post or pier type structure allows the repair structure to have footing on uneven surfaces or bridge over rough sections.

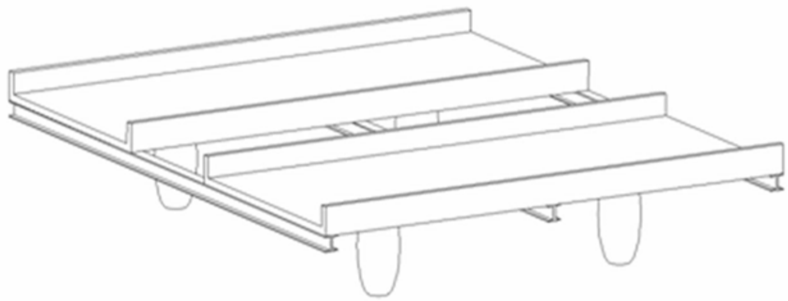


Figure 21 Wheel Track and Rails with Epoxy Pier Supports

A Truss structure combined with the Wheel Track driving surface, could provide a support frame for the driving surface in much the same way the rail/girder would function. The Truss support frame could be used with a vertical post support or with a permanent or folding trestle. The benefits of the truss frame and trestle support may not be worth the possible complexity of its design and construction. The final combination, Wheel Track and None/Integrated support would work fine for crossing smaller cracks where stability was not an issue and if the wheel tracks were strong enough to function without an additional frame.

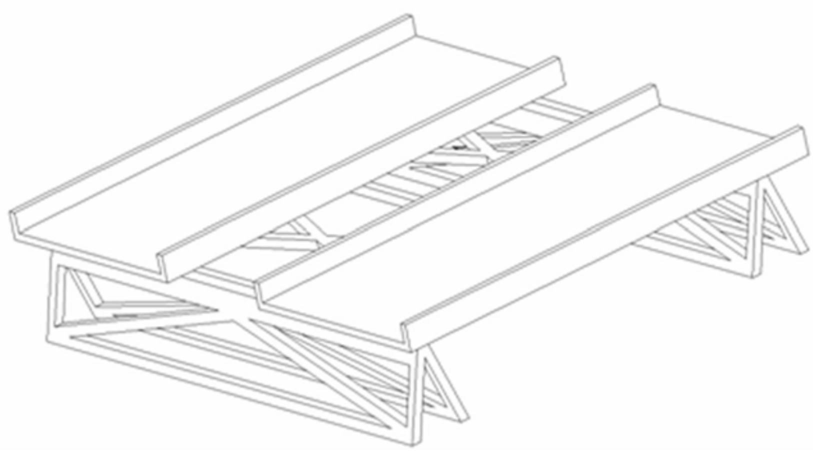


Figure 22 Wheel Track and Truss Combination

Plank:

The first Plank driving surface combination is with the Trailer. This combination requires the trailer to have a complete support structure to attach the planks to. Although this combination is possible, there are other driving surfaces that work better with the trailer, as there are no distinct advantages to using planks. The strong points of using a plank driving surface, easy storage and a driving surface that can twist to accommodate skewed road surfaces, are negated when attaching the planks to a trailer structure.

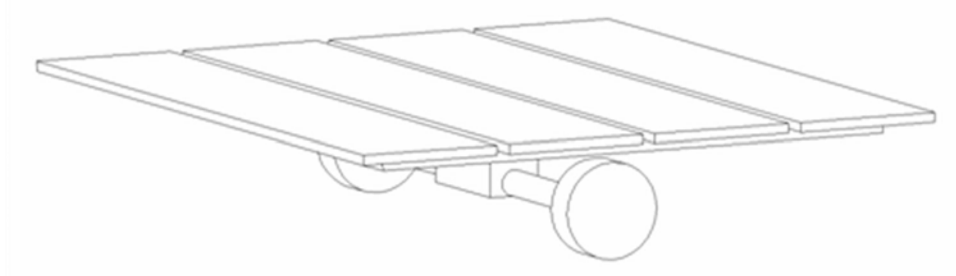


Figure 23 Plank and Trailer Combination

The second combination is the Planks with the Rail/Girder support structure. These two work together pretty well, forming a system where the rails run under the plank driving surface providing support for vehicle loads. If the plank attachment points to the rails were designed in such a way to allow for some movement, the two rails might be raised to different heights allowing the repair structure to twist slightly. This would be helpful in situations where the structure was being used as a ramp up to a higher surface that was not parallel with the lower surface.

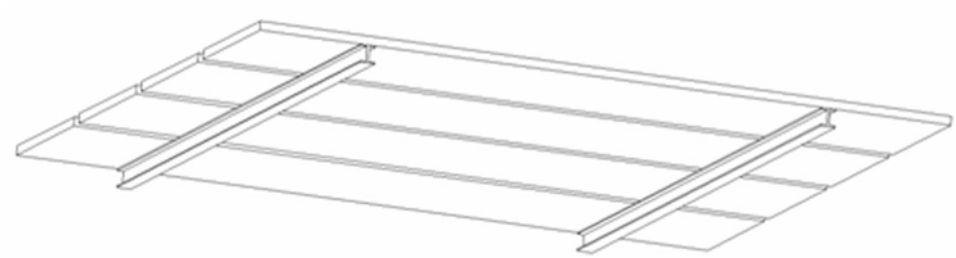


Figure 24 Bottom View of Plank and Rail Combination

The combination of the Planks and Post/Pillar is shown in one possible embodiment. The illustration shows the planks held between two outer support beams that also contain attachment points for the vertical posts. This scheme has the advantage of being highly collapsible for storage but would require assembly at the repair site. Also this set up requires stronger planks than other combinations because they are used to support the full load of the vehicle.

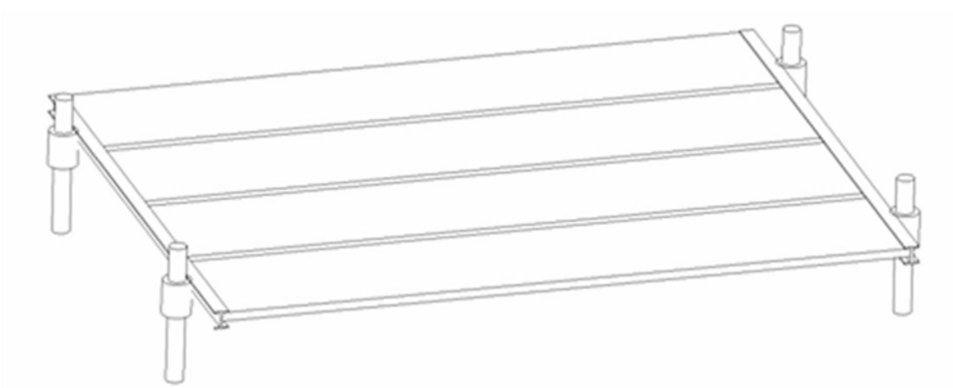


Figure 25 Plank and Vertical Post/Pillar Supports

The combination of the Planks and Truss/Trestle ideas are shown. The truss frame and trestle supports will work fine as a support structure for the planks but again it seems as if the benefits of the plank driving surface are not being utilized with this combination. Additionally, extra time might be required to assemble a plank driving surface with a truss frame.

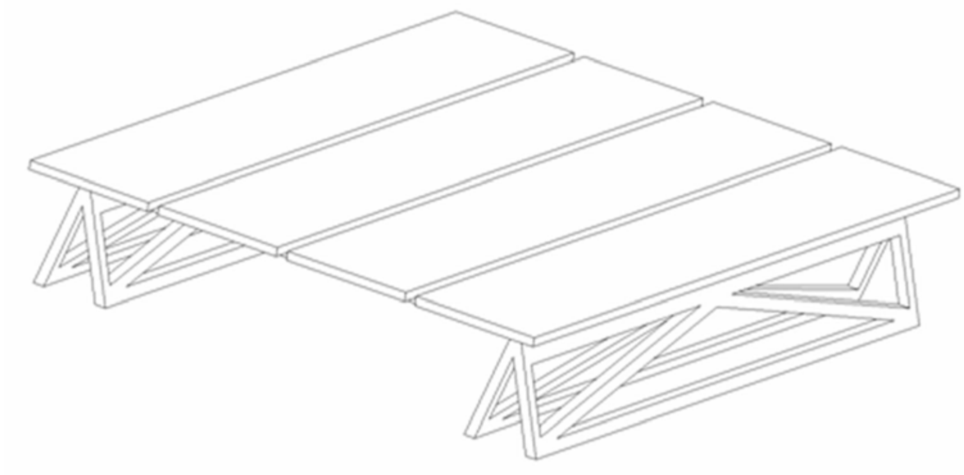


Figure 26 Plank and Truss Combination

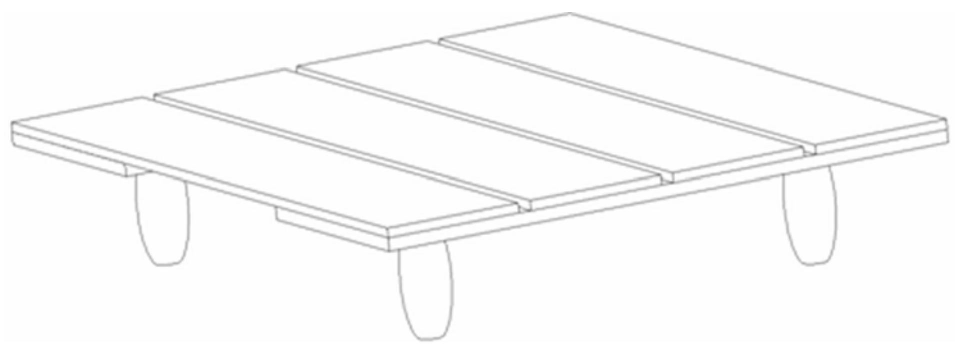


Figure 27 Plank and Epoxy Pier Combination

Shown is a possible method for using Planks with Epoxy Pier supports. This system is similar to the Plank and Rail/Girder combination except the support beams under the wheel path are designed to have broader flat attachment points for the epoxy piers. This design could also perhaps be made to accommodate some support beam twisting. Otherwise it seems a lot like an upside down wheel track, with the beams that run in the direction of traffic under the wheel paths supporting most of the load and the planks mostly maintaining their spatial relationship. Since the planks run perpendicular to the direction of traffic, they would not be of much use without a support structure and have not been drawn combined with the None/Integrated option.

Plate:

The next set of idea combinations starts with the Plate driving surface and the Trailer support structure. This combination is similar in many ways to the combination of the Wheel Track and Trailer, having many of the same strengths and weaknesses. A main difference is that a plate would not restrict vehicle travel across it to certain direction. As an example, a vehicle must be in line with the wheel tracks to pass over the Wheel Track driving surface whereas it would be possible to cross a plate driving surface at any angle.

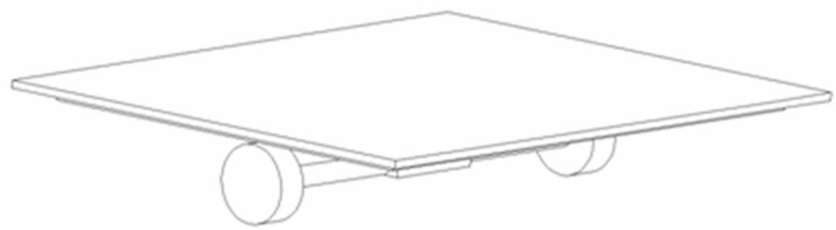


Figure 28 Plate and Trailer Combination

The Plate and Rail/Girder combination could be constructed and would allow for thinner lighter weight plates but other than this would not have many advantages over just using a plate alone, as the Plate and None/Integrated support option shows.

Figure 29 Plate and Rail Combination

The illustration for the Plate and Post/Pillar combination shows a configuration that would rely on a structurally strong plate to carry the vehicle loads, where the vertical supports are mostly used for height adjustment. Having the post attachment points located under the probable vehicle wheel paths as in the Plate and Epoxy Pier drawing would allow the vertical supports to carry more of the load. Of course placing the post/pillar under the plate introduces some issues about height adjustability and method of attachment.

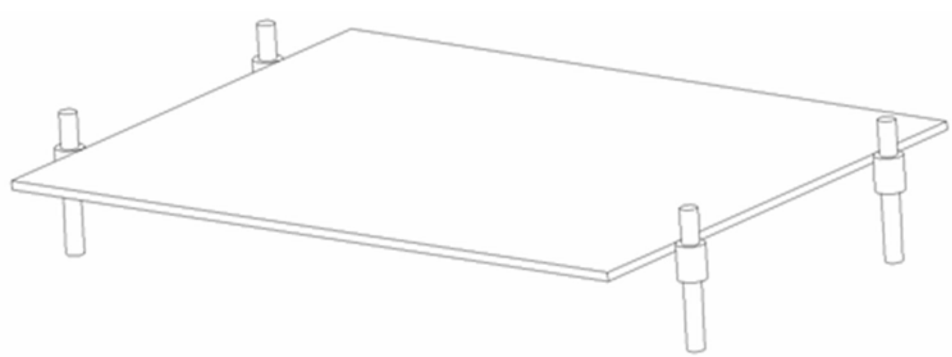


Figure 30 Plate and Vertical Post/Pillar Supports

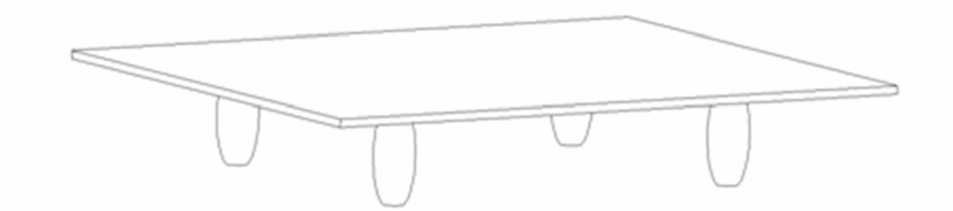


Figure 31 Plate and Epoxy Pier Vertical Supports

The Plate and Truss/Trestle combination shown illustrates a case where the plate is strong enough that it does not need a truss support frame and uses the trestles for height. Although this setup would work, it is slightly inferior to using posts or pillars because of its diminished height adjustment possibilities.

Figure 32 Plate and Truss Combination

Bridge:

The Bridge Driving Surface idea is different from the other driving surface ideas in that they are all flat sections while the Bridge contains an arch or raised center section. Because of the way the Bridge idea is laid out, lower ends and raised middle, its combination with the Trailer will need to be raised in order to keep the ends sufficiently high off the ground. While it might be easy to tow the Bridge and Trailer combination to the repair site and even set it up by lowering the unit over small to medium sized cracks and steps, it might be very difficult and awkward to orientate it to cover a large surface faulting step.

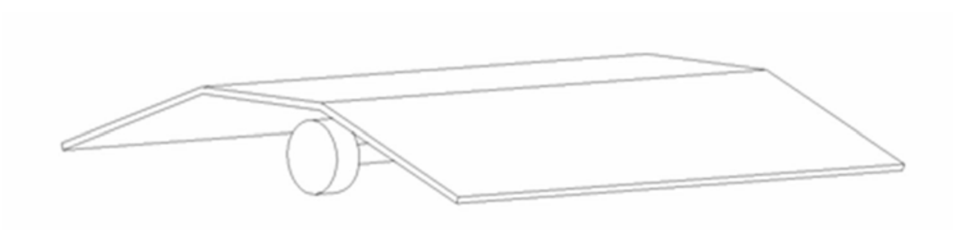


Figure 33 Bridge and Trailer Combination

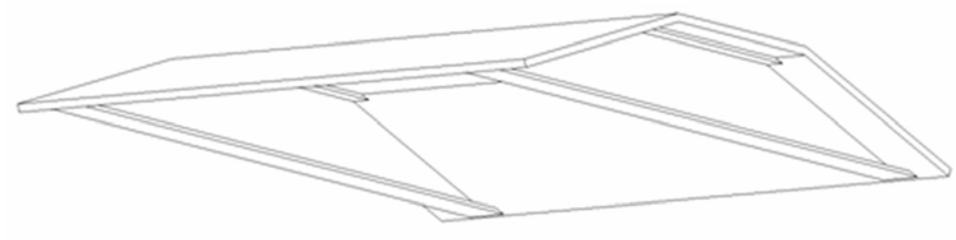


Figure 34 Underside of Bridge and Rail Combination

Figure 35 Bridge and Truss Combination

Having the Bridge driving surface combined with either a Rail/Girder support or Truss support structure under it seems to make the most sense. Both of these combinations allow for a driving surface and support combination that could feature one or two hinging areas, allowing the bridge to fold for transport. Both the Bridge and Post/Pillar and the Bridge and Epoxy Pier combinations would rely on vertical supports under the center or middle section to provide the support for the arch, essentially like a bent plate with support in the middle. An arched driving surface needs some sort of support and does not make sense without it, and therefore the Bridge driving surface has not been drawn with the None/Integrated option, although by its nature most of the combinations feature an "integrated" support.

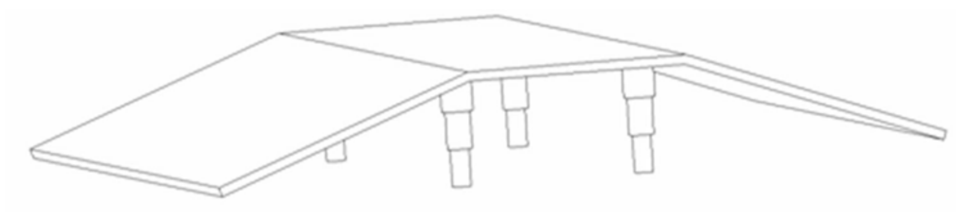


Figure 36 Bridge and Vertical Post/Pillar Support

Mat:

The Mat Surface and it accompanying combinations are of a slightly different nature than the previous sets of combinations, due mostly to the idea of having a non-rigid driving surface. For instance there does not appear to be a good reason or way to combine a non-rigid Mat driving surface with a Trailer support structure so this combination has been left without a drawing. Similar reasoning exists in not presenting drawings of a Mat driving surface combined with either a Post/Pillar or Epoxy Pier support structure. Both of these support structure ideas rely on a rigid driving surface to fasten to, which the Mat driving surface alone does not have.

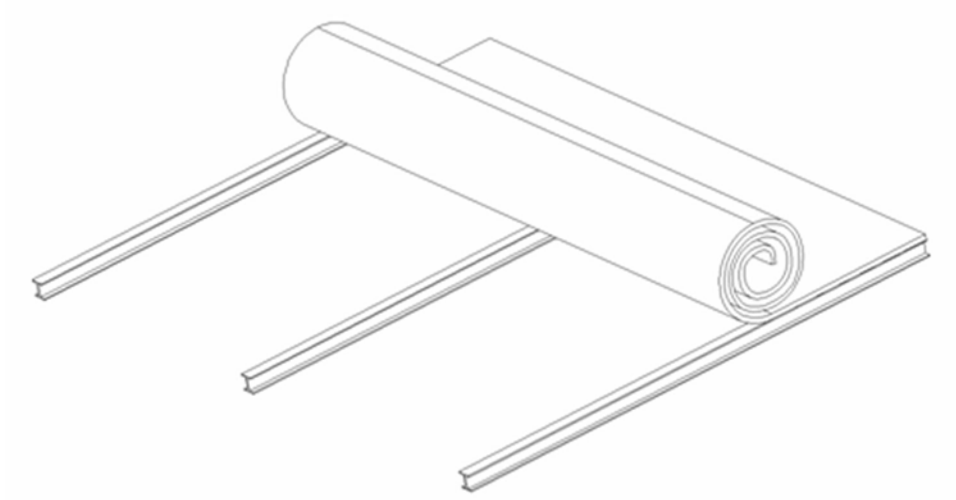


Figure 37 Mat Combined with Rails for Support

A Mat used in conjunction with the Rail/Girder or Truss frame support could utilize a vertical post type support. The figure shows the combination of the Mat and Rail/Girder support structure idea. Unless the Mat is laterally very rigid, additional cross bracing would probably be necessary to secure the structure. This would basically result in a combination of a Mat Driving Surface and a Truss/Trestle support frame. A truss support frame would not necessarily have to use a trestle type vertical support but could utilize either a Post/Pillar or an Epoxy Pier setup. The real strength of the Mat driving surface idea comes more for its ability to roll up for storage and work with the None/Integrated option providing stable vehicle crossings over loose and otherwise unstable soil either alone or as an approach to other repair structures.

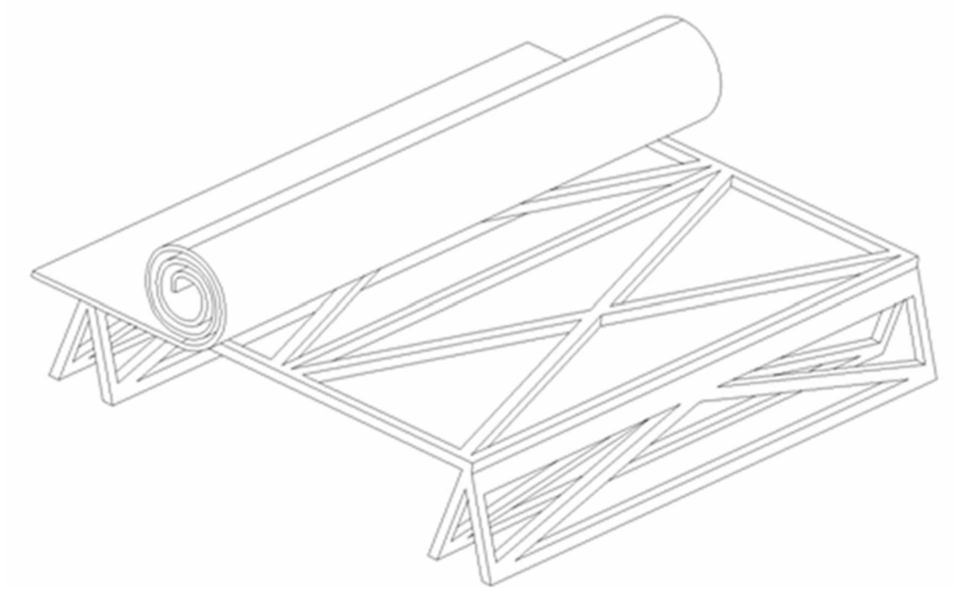


Figure 38 Mat and Truss Combination

The complete list of driving surface and support structures has a total of 30 possible combinations. After going through the process of drawing out the combinations and thinking through their application, it is clear that some combinations can be removed as illogical or unnecessary. For instance, while the Wheel Track and Rail/Girder combination could work together, but the repair structure combination of Wheel Track and Post/Pillar encompasses that idea of the first combination. Elimination was done by marking all of the combinations on the list with either a minus, a check or a plus, depending upon the structure combination's feasibility and effectiveness, and removing all 10 combinations marked with a minus. At this point it was noted that the Post/Pillar design choice was essentially the same as the Epoxy Pier design choice, the differences being mostly in their adjustment and deployment options. So for the sake of reducing numbers, the two options were combined. Additionally it was noted that the None/Integrated support choice is more of a deployment option available to some of the driving surfaces rather than a design choice. For instance a Plate and Post/Pillar design could still be deployed without the supports, utilizing only the plate for simple repairs. Accordingly, the combinations on the list with the None/Integrated support choice were also removed from the list, leaving 14 combinations. At this point, the combinations with check mark ratings were eliminated and the most promising 7 of the plus marked options were selected. These final 7 were Wheel Track and Trailer, Wheel Track and Post/Pillar/Pier, Planks and Rail/Girder, Plate and Trailer, Plate and Post/Pillar/Pier, Bridge and Truss Trestle, and finally Mat and Truss/Trestle.

Repair Structure Selection

At the point of having reduced the repair structure choices from 30 possible down to 7 remaining combinations, using both logical and subjective choices, a set of criteria was established by which to judge the final 7 driving surface and support structure combinations. This judgment criteria was developed keeping in mind the General Repair Parameters and the Main Functions points. The Criteria, broken into three sections, Design Objectives, Physical Constraints, and Use Parameters.

Judgment Criteria

Design Objectives	**Physical Constraints**
Must effectively open damaged roads	Self-contained
Low enough cost to have at several locations	Size of structure
Least number of operators	Weight of structure
Operates with non-specialized personnel	Number of pieces of equipment
Robust and reliable even after long inactivity	Number of units that can be stored
Ability to use with no supports	Storage space
	Drivable Area
Use Parameters	Accommodate all types of damage
Ease of transportation	Size of repair
Ease of assembly	
Ease of mobility	
Ease of placement	

Table 10 Judgment Criteria

Using all of the criteria to judge the concepts at this stage of infancy would greatly increase the amount of guessing and estimation so only the most general criteria were selected for use in the Selection Matrix. The criteria used included all of the “Use Parameters,” many of which encompass some of the more detailed criteria. For example, the “ease of transportation” parameter would depend on many things like the weight and size of the structure, as well as the storage space required and the number that can be stored during transport. Also included in the selection matrix was the “ability to use with no supports,” since it had previously been eliminated as a design choice it was now included as a desirable quality that some of the concepts possessed. The “number of pieces of equipment” was also included because it was felt that this criteria could accurately be judged at this point in the concept development. Additionally, it has many ramifications as to the complexity of the repair structure and its assembly time. All of the criteria used were weighted on a scale of 1 to 5 with 5 being the most important. The repair structure concepts were then compared to the criteria and scored. The following table shows the outcome.

Selection Matrix

Criteria	Weight	Track & Trailer		Track & Post		Plank & Rail		Plate & Trailer		Plate & Post		Bridge & Truss		Matt & Truss	
Ability to Use with No Supports	1	0	0	1	1	0	0	0	0	1	1	0	0	1	1
Number Pieces of Equipment	3	3	9	4	12	1	3	3	9	4	12	4	12	2	6
Ease of Transportation	3	5	15	4	12	4	12	5	15	4	12	2	6	4	12
Ease of Storage	3	3	9	4	12	5	15	3	9	4	12	1	3	3	9
Ease of Assembly	3	5	15	3	9	2	6	5	15	3	9	5	15	1	3
Ease of Mobility	2	4	8	2	4	2	4	4	8	3	6	1	2	2	4
Ease of Placement	4	3	12	3	12	4	16	2	8	2	8	2	8	3	12
	Sum	23		21		18		22		21		15		16	
	Weighted		68		62		56		64		60		46		47

Table 11 Selection Matrix

After looking at the selection matrix and the weighted scores, it is clear that some of the concept combinations stand out. The Wheel Track and Trailer concept scored the highest, followed closely by the Plate and Trailer, the Wheel Track and Post/Pillar/Pier and the Plate and Post/Pillar/Pier. The other three concepts, Planks and Rails, Mat and Truss, and Bridge and Truss all scored a bit lower. Not all that surprisingly, the four concepts that scored highest are all pretty similar and even somewhat interchangeable, the driving surface of either a Plate or Wheel Track can be used with either a Trailer or a Post/Pillar/Pier set up. In fact, a trailer system would need to have some type of vertical post like support for leveling and stabilization. The main difference between the Trailer and the Post/Pillar/Pier configurations is in their deployment method; once the repair structure has been set in place they are quite similar. Because of this it may be possible to come up with some sort of hybrid structure that mixes the concepts, allowing the repair structure to work either way, taking advantage of the Trailer concept's ease of transportation and the Post/Pillar/Pier adjustability. Both of the two selected types of support structures, Trailer and Post/Pillar/Pier, can have adjustability implemented with any one of the six adjustment types. The adjustment systems are Air Bags, Screw Jacks and Spiral Lifts, Ratcheting Jacks, Scissor Jacks, Hydraulic or Pneumatic Pistons, and Fixed or Externally Adjustable. The decisions on which adjustment type and method will work the best will be based on comparing the design concepts and their use in selected damage scenarios.

Conceptual Design Selection

At this point in the design process, the repair structure design concept has been narrowed down to four combinations consisting of one of two Driving Surfaces, a Wheel Track or a Plate, and either of two Support Structures, a Trailer or a Post/Pillar/Pier support. Of the overall conceptual design for the repair system, several of the functional areas still need to be considered. The categories that still remain to be addressed are the Adjustment methods, the categories concerning the deployment and the transportation of the repair structure.

The morphological chart lists six options in the Adjustment category that can be combined with the structure. The Deployment section has three categories with six options in the Unloading category, another six options in the Positioning category, and four more options in the Alignment category. The Unloading category refers to the process of removing the repair structure from its stored position, the Positioning category refers to getting the repair structure orientated and placed for the repair, and the Alignment category refers to operations relating to correctly setting the repair structure with regard to its height and relationship to the ground and other structures.

Not including the transportation options, the choices for the conceptual design in the Structure, Adjustment, Unloading, Positioning and Alignment categories, result in a large number (3456) of possible combinations, once again too many to consider one at a time. An alternate method for making an informed choice on the conceptual design, rather than going through the entire set of combinations individually, is to investigate how each of the four repair structure combinations perform in different damage cases. This process will help illustrate the importance of adjustment and deployment methods and also shows how they might be employed. It will also show in what cases adjustment comes into play and how it best works with the structures. This process of comparing the repair structures and their setup options to different damage cases will provide enough information to narrow down the conceptual design to one repair structure and adjustment concept. Another purpose is to establish clearly how each of the repair structures will be used, as their use will vary depending on the nature of the repair. This factor will largely affect decisions about how the repair structures will be deployed.

Damage Criteria

For the purpose of evaluating how each of the repair structure combinations might function in the broad range of repair situations occurring after an earthquake, a set of damage scenarios has been selected. The set of damage scenarios has been selected to represent the range of repairs that might be encountered, ranging from relatively simple cracks to complex vertical offsets and buckled road surfaces. The discussions of how each structure and deployment combination might be used for the different damage cases is helpful in discerning the particular advantages and negative aspects of each repair structure, as some work better for certain types of damage but are less effective for other types of damage.

The damage scenarios range from mundane road cracks to large-scale liquefaction and surface faulting. The easier to repair damage cases involve cracks and steps perpendicular to the direction of vehicle travel and road surfaces that are parallel to each other. Cases with increased repair difficulty have the cracks and vertical steps crossing the direction of vehicle travel at sharp angles. The level of repair difficulty is increased again when the damage includes skewed road surfaces that are not parallel to each other. All of the damage cases assume that the repair is taking place on a level roadway. Inclined or sloped roads will increase the level of repair difficulty. Following are a basic set of damage cases and relative sizes. Since no one can actually predict what is going to occur as the result of an earthquake, the cases and values represent a best estimate based on currently available research.

Damage Cases Listed in Order of Increasing Difficulty

1	An open crack (gap) perpendicular to the direction of travel on a level section of road
2	Cracked and broken road surface
3	A vertical step perpendicular to direction of travel with both surfaces level
4	A buckled section of road perpendicular to the direction of travel.
5	A vertical step crossing the direction of travel at an angle with both surfaces level
6	A vertical step perpendicular to direction of travel where surfaces are not parallel
7	A buckled section of road crossing the direction of travel at an angle
8	A vertical step crossing the direction of travel at an angle where surfaces are not parallel

Table 12 Damage Cases Listed in Order of Increasing Difficulty

The predicted moment magnitudes for future Bay Area earthquakes can be used with the Eqns (1) through (6) from the previous chapter to calculate the estimated damage sizes for surface faulting road closures. The predicted earthquakes for the 18 different fault rupture scenarios have moment magnitudes that range from a smallest magnitude of 6.2, to a largest of 7.9, the median value of the set is 6.85, the average is 6.88 and the most commonly occurring earthquake moment magnitude value is 6.9.

Representative Damage Sizes for Surface Faulting

Small (6.2) Max	Horizontal = 0.23 m [0.74 ft]
	Vertical = 0.08 m [0.25 ft]
Medium (6.9) Max	Horizontal = 1.19 m [3.92 ft]
	Vertical = 0.40 m [1.3 ft]
Large (7.9) AVE	Horizontal = 6.17 m [20.23 ft]
	Vertical = 2.06 m [6.74 ft]
Large (7.9) Max	Horizontal = 12.79 m [41.97 ft]
	Vertical = 4.26 m [13.99 ft]

Table 13 Representative Damage Sizes for Surface Faulting

The values for the damage sizes due to liquefaction are based not on earthquake moment magnitude, but on the depth of the fill where the liquefaction takes place. The fill depths shown were selected to show a range of damage sizes. The horizontal movement and possible accompanying cracks are calculated as 30% of the fill depth, vertical settlements are calculated as 5% of fill depth.

Representative Damage Sizes for Liquefactions

Small, 2.4 m [8 ft] fill	Horizontal = .73 m [2.4 ft]
	Vertical = .12 m [0.4 ft]
Medium, 4.9 m [16 ft] fill	Horizontal = 1.5 m [4.8 ft]
	Vertical = .24 m [0.8 ft]
Large, 7.3 m [24 ft] fill	Horizontal = 2.2 m [7.2 ft]
	Vertical = .37 m [1.2 ft]

Table 14 Representative Damage Sizes for Liquefactions

Damage Cases

The following section contains short descriptions of the eight damage cases along with an illustration of each. The descriptions are organized in the order of increasing repair difficulty.

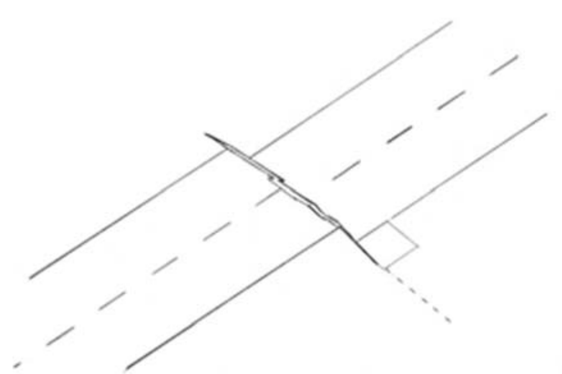


Figure 39 Perpendicular Crack

An open crack (gap) perpendicular to the direction of travel on a level section of road – This is the simplest type of damage to repair because there really is no need for a structure that has any height to it. In other words, a suitable driving surface that can be placed over the crack is all that is necessary for the repair.

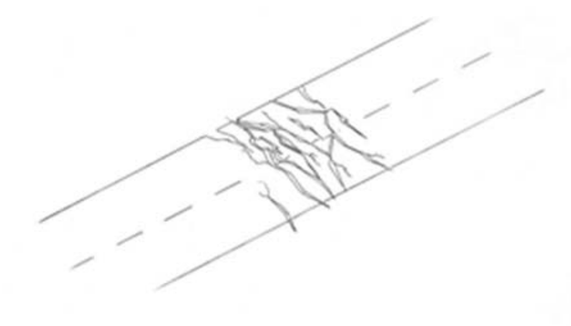


Figure 40 Broken Road Surface

Cracked and broken road surface – This is listed as being more difficult than a single crack because the broken road surface might require the repair structure to have some sort of support for stabilization. This type of damage might be the result of liquefaction or horizontal displacement, where there is insignificant vertical displacement but the road surface is damaged from the shifting ground. Cracked and broken road surfaces may be found in conjunction with many of the more severe damage types.

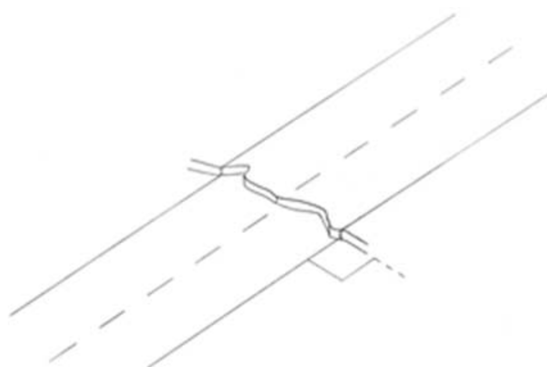


Figure 41 Step Perpendicular to Road

A vertical step perpendicular to direction of travel with both surfaces level – This is the first damage case in this list to have a substantial vertical component, requiring that the repair structure gain height at some point so that traffic may drive either up or down the vertical step.

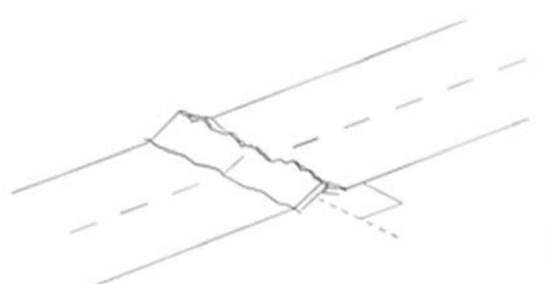


Figure 42 Buckle Perpendicular to Road

A buckled section of road perpendicular to the direction of travel – This damage case is considered more difficult to repair than a step because a buckled section of road will require that the repair structure be positioned not only to let vehicles get up the obstacle as with a vertical step, but also down again on the other side.

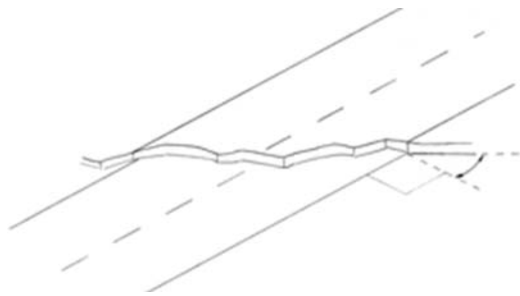


Figure 43 Angled Step Crossing the Road

A vertical step crossing the direction of travel at an angle with both surfaces level – The damage cases from this point on are no longer unique but rather more complicated configurations of vertical offsets and buckled road surfaces. Anytime a crack, vertical offset or buckled section crosses the road at a sharp enough angle, it can force the repair structure to no longer be set up orthogonal to the damage. This effectively lengthens the amount of necessary repair coverage. This particular case has the vertical step crossing the road at a sharp angle. This will require repair structures to either approach the step also at an angle or to use supports of different lengths to account for only part of the structure being on the upper level.

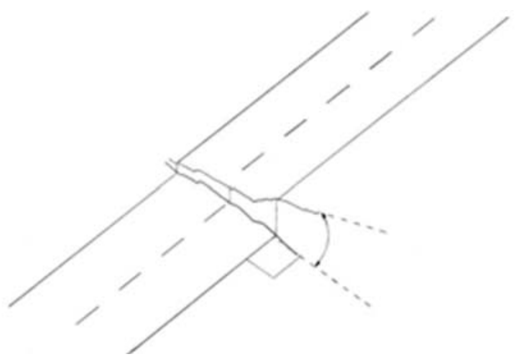


Figure 44 Step with Non-parallel Road Surfaces

A vertical step perpendicular to direction of travel where the two surfaces are not parallel – The difficulty in dealing with this damage case comes from having to place the repair structure onto two uneven surfaces. This will introduce problems with getting the structure to remain stable (to not rock) and with providing good close mating edges where the vehicle drives onto or off of the repair structure.

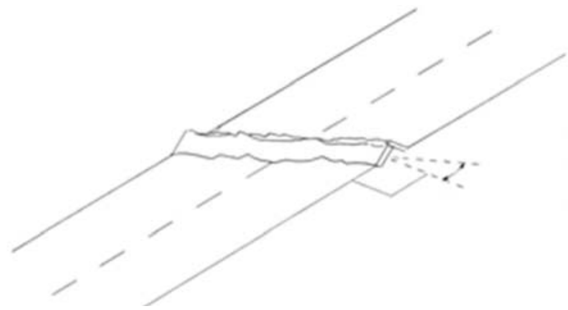


Figure 45 Road Buckle at an Angle

A buckled section of road crossing the direction of travel at an angle – This is another damage case where the damage, a buckled road section, is crossing the road at a sharp angle. In this situation, depending on the size and orientation of the road surface buckle, the repair structure will need to bridge up, over and down the other side. This will present problems not only in where the structures are placed, but how they are deployed.

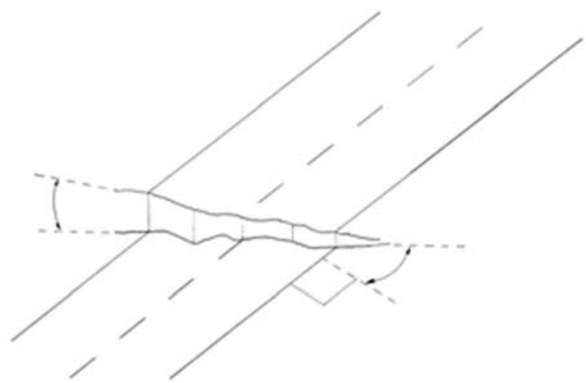


Figure 46 Angled Step with Non-parallel Road Surfaces

A vertical step crossing the direction of travel at an angle where surfaces are not parallel – This last damage case combines the difficulties of both a damaging vertical offset crossing the road at a sharp angle and having to place the repair structure on two uneven surfaces. Depending on the severity of the damage, the angle at which it crosses the road and the degree to which the two road surfaces are uneven, several repair structures may be necessary to completely create a safe vehicle path.

Deployment Scenarios

Since some of the damage cases are just combinations of two simpler cases, it makes sense that descriptions of the repair structures use for each of eight scenarios may be redundant in some of the instances. For example, the final damage case, a vertical step crossing the direction of travel at an angle where the two road surfaces are not parallel, is really a combination of the vertical step crossing the road at an angle and the vertical step perpendicular to the direction of travel but with uneven road surfaces. Any repair structure able to deal with the more complex final case will also be able to handle the repairs of the two cases of which the final is a composite. This same line of reasoning was applied to the two damage cases that involve buckled road surfaces. The only difference between the two cases is the angle at which the line of buckling crosses the road. If the repair structure is able to repair the more complex case where the buckle crosses the road at a sharp angle, the simpler case where the buckle crosses the road at a right angle should not present a problem.

The following paragraphs contain descriptions of how the four different repair structures would best be used in each of the five selected damage repair scenarios. The descriptions are organized by damage case, with a section on each of the four repair structures and its repair scenario.

PERPENDICULAR CRACK

Wheel Tracks & Trailer – This repair is simple with the use of a Wheel Track and Trailer combination. As long as the crack or gap is not significantly longer than the reach of the trailer, the repair structure could be driven up to one side of the crack. Once in place, the Wheel Track driving surface could be expanded to the desired width, and additional supports would be attached if they were not permanently part of the repair structure. Putting down additional supports stabilizes the driving surface and provides a means for leveling it. Any of the Adjustment types (Air Bags, screw, ratchet or scissor Jacks, pneumatic or hydraulic Pistons) would be suitable to aid in the leveling process, although having the adjustment built into the vertical supports would probably be the simplest. Once in position the trailer tongue could either be removed or adjusted out of the way via a telescoping rod. Ramps leading up to the Wheel Track driving surface could be attached or if already part of the structure, flipped down into the use position. Drawbacks to this setup include the use of supports for stability in addition to the trailer itself and the apparent excess of using such a large structure for a simple damage type.

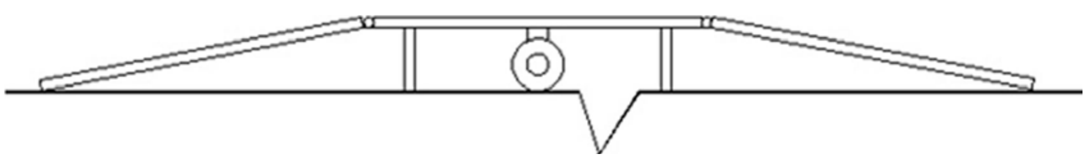


Figure 47 Basic Trailer Setup for Simple Cracks

Plate & Trailer – Because the Plate and Trailer is so similar to the previous Wheel Track and Trailer combination, it would be used in nearly the exact same manner. This includes the use of additional supports to level the driving surface and the adjustment method, although the attachment points for the supports and adjustment could be different. Another difference is that the wheel track has the option of being collapsible while the plate is a rigid structure. The reason this might be an issue is if the desired width of the structure is equal to a typical traffic lane, 3.7 m [12 ft] wide, it would be too wide to tow. The maximum vehicle width is 2.4 m [8 ft], so in order to have the plate a legal tow vehicle, it would need to be towed with its 2.4 m [8 ft] length oriented width wise and then pivoted around 90° at the time of deployment so that the wider 3.7 m [12 ft] side would be the width when positioned. Again, like the Wheel Track and Trailer, this repair structure is far more than the minimum necessary to repair a simple open crack in the road.

Wheel Tracks & Post/Pillar/Pier **–** Using the Wheel Track and Post/Pillar/Pier structure to repair a gap crack in the road could happen in a couple of different ways. First, if the road is level enough, the driving surface alone, the Wheel Tracks, could be placed over the road damage, requiring only that the wheel track spacing be adjusted if necessary. The only question concerns the placement of the Wheel Tracks. This could be anything from as simple as flopping them off the bed of a truck to a more precise use of a boom arm or crane to lower them into place. For this small type of road damage, supports and adjustments may only be necessary to prevent the Wheel Tracks from rocking. If the Wheel Tracks have permanently attached supports, more care will have to taken when deploying the structure and ramps may have to be used if the driving surface cannot be lowered close enough to the road. Also, since the wheel track is bi-directional it needs to be lined up with the direction of traffic.

Plate & Post/Pillar/Pier – The Plate and Post/Pillar/Pier combinations will function in much the same way as the Wheel Track and Post/Pillar/Pier, needing only the plate for this simplest repairs with added supports to inhibit rocking in other cases. Also, the same issues exist with deploying the plate, and because the size of the plate cannot be adjusted, it may be a bit more unwieldy during deployment. The plate has the added advantage of not needing as much care in lining it up with the direction of traffic because vehicles can cross it in any direction and are not restricted to staying within the wheel tracks.

<u>BROKEN SURFACE</u>

Wheel Tracks & Trailer **–** The Wheel Track and Trailer structure combination could have trouble with this repair, depending on how broken up the road surface is and the length of the damage. If the driving surface with the ramps deployed is long enough to bridge over the entire damaged area, the trailer unit could be placed in the center of the broken area, with the ramps reaching undamaged road on either side. A longer stretch of damage might require multiple repair structures linked together. The following figure illustrates both types of setup. A badly cracked and disfigured road surface could prevent the trailer from being easily towed or pushed into position in the center of the damage. For a section of damage only requiring one Trailer unit for a complete repair, a set of ramps or a second Trailer unit could be used to create a path to the center of the damaged road section, where the Trailer and driving surface would be deployed. Another method that could be used with only one Trailer might include anchoring a pulley on the far side of the damage and using a winch to get the Trailer and driving surface into place. Once in place vertical supports with adjustments would have to be used to level off and stabilize the driving surface.

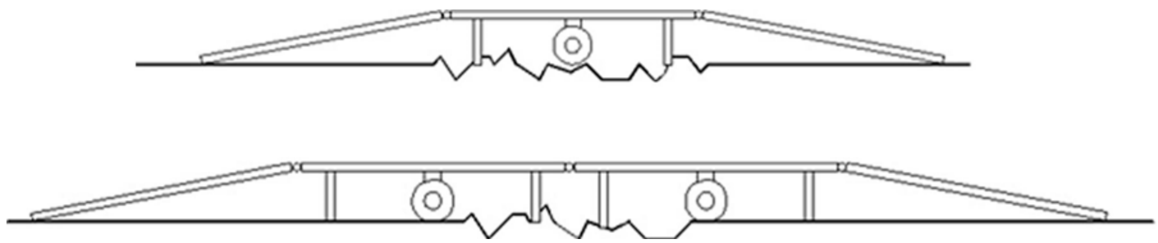


Figure 48 Single and Dual Trailer Setups

Plate & Trailer – Using a Plate instead of Wheel Tracks as the driving surface combined with the Trailer, provides no distinct differences in usage. Essentially the same problems and solutions would exist for placing the Trailer unit in the middle of the broken and damaged road surface. Supports would also have to be used for leveling and stabilization and ramps utilized for getting vehicles up to the Plate and down the other side.

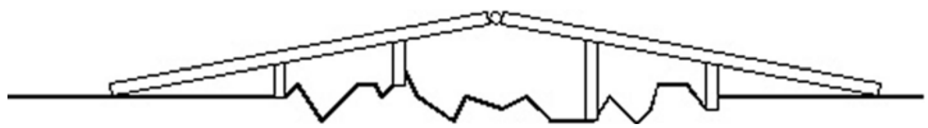


Figure 49 Angled Setup Over Broken Road Surface

Wheel Tracks & Post/Pillar/Pier – Using Wheel Tracks to cross the cracked and damaged road surface can be done in one of two ways, both of which make use of the Post/Pillar/Pier supports for leveling and stabilization. One way is to use two Wheel Track driving surfaces, with the trailing edge of the first Wheel Track driving surface resting on the undamaged road just before the beginning of the cracking. This Wheel Track will be raised at a slightly sloping angle and held up with the Post/Pillar/Pier supports. At the highpoint, the leading edge of the structure will meet the edge of the second Wheel Track that is positioned in a mirror image fashion, sloping down again to the undamaged road surface past the cracked area. This configuration could be set up by using a crane or boom arm to place the plates in the correct spot. If the Wheel Tracks already had the supports attached, it would then be a matter of adjusting their lengths to get the two driving surfaces to sit properly. Alternately, the crane or boom arm could be used to hold the Wheel Track in the correct position while the supports were attached. Care will have to be taken when positioning the driving surfaces to assure that the angle of inclination is shallow enough to prevent crossing vehicles from high centering on the ridge where the two the driving surfaces come together. The second repair configuration is to use one Wheel Track driving surface set up flat and slightly raised in the middle of the damaged road surface area. From the undamaged road surface, ramps or other sets of Wheel Tracks will lead up to and down the other side of the elevated Wheel Track. This set up would look similar to the driving surface and Trailer combinations.

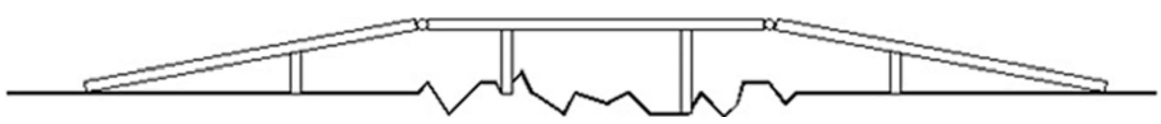


Figure 50 Repair Setup for Longer Span

Plate & Post/Pillar/Pier – The way that the Plate and Post/Pillar/Pier combination would be used on this type of damage is identical to either of the two ways the Wheel Track and Post/Pillar/Pier could be set up. The only differences might occur in the type of supports used, their attachment, and the deployment method, since this is a plate and not a set of wheel tracks.

PERPENDICULAR STEP

Wheel Tracks & Trailer – In this damage scenario, the difficulty level of doing the repair with the Wheel Track and Trailer largely depends on the direction from which the damage is approached. Approaching the vertical step from the lower side allows the trailer to be wheeled right up to the step, where it can then be secured with additional supports and the ramps put in place. The exact configuration of the trailer and ramps will depend on the height of the step relative to the height of the trailer. If the Wheel Track driving surface is higher than the upper level of the step, then the trailer can be pushed right up to the step, with much of the driving surface hanging over the upper level. Ramps will be placed on both sides allowing vehicles up onto and off of the driving surface. If the step height is very close to the Wheel Track height, the repair structure can be placed with one edge resting on the upper step surface and with ramps only on the one side leading up. When the step being repaired is higher than the Wheel Track driving surface, the repair structure will be positioned so that ramps on the step side of the driving surface will reach up from the driving just to the edge of the step. When the step is approached from the other direction, the higher side, some method will have to be used to get the repair structure to the lower side of the step. This might involve using ramps to wheel the trailer down, rails to slide the structure down, a winch to control the lowering of the structure, or perhaps if designed in a robust way, the trailer could be simply be pushed over the drop. Regardless of the technique used, the trailer will need to find its way to the lower side of the step where it will be positioned in one of the ways previously described.

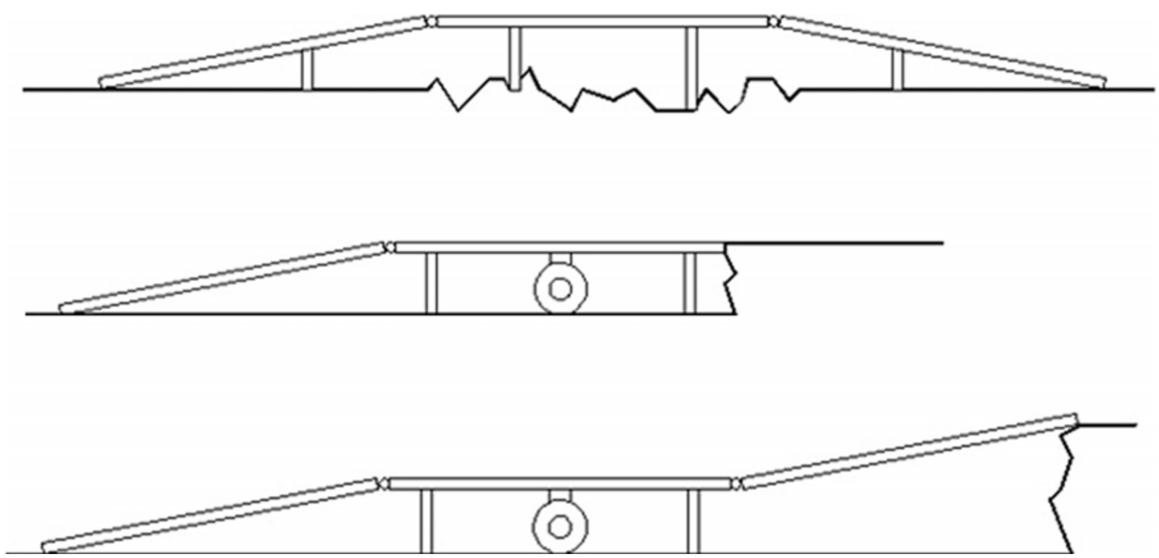


Figure 51 Trailer and Ramp Setups for Varying Step Heights

Plate & Trailer – A Plate and Trailer combination would be used in the same manner for a vertical step type of damage. The same increased difficulties would be encountered when approaching the step from the upper side, because just as with the Wheel Track and Trailer combination the structure needs to be on the lower level portion of the road to complete the repair. The fact that the Wheel Track width can collapse some for transportation and that the Plate rotates to orientate the correct width to the traffic, might make one type of driving surface and Trailer combination easier to negotiate down the step than the other.

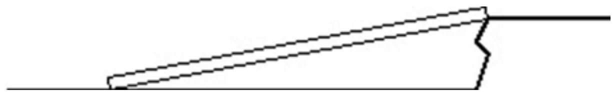


Figure 52 Single Driving Surface Setup

Figure 53 Post/Pillar Setup Over Low Step

Wheel Tracks & Post/Pillar/Pier – The Wheel Track and Post/Pillar/Pier combination can be used in a couple ways. If the resulting incline is not too steep, more than 20% slope, the Wheel Tracks alone can be placed directly on the step in a ramp like fashion, or the structure with supports can be placed level, before or over the step, with ramps connecting the Wheel Track to the lower and upper step levels. Using a driving surface with Post/Pillar/Pier supports alleviates some of the problems that the Trailer structures have when approaching a step from the upper level. Because the wheel tracks need to be deployed off of the transportation vehicle anyway, performing this operation from either the upper or lower side of the step should not make much of a difference. If the wheel track does not have supports that are permanently attached, there are three main times when the attachment could be done. The supports could be attached before, during or after deployment. Attaching supports before deploying the driving surface would allow the Wheel Track to simply be deployed and then adjusted. Attaching the supports during deployment could take place by having a boom crane or lift arms hold the driving surface in the correct position while the supports were attached. This has the advantage of allowing the Wheel Track position to be independent of the road damage until the supports are put in place, and does not require that the supports be adjustable once their height is set. Attaching the supports after the deployment would require that the supports be adjustable, allowing them to be used for raising and positioning the driving surface.

Plate & Post/Pillar/Pier – Using a Plate instead of Wheel Tracks as the driving surface combined with the Post/Pillar/Pier supports would not change much in the way the repair structure is used. In fact all of the same issues regarding positioning and deployment would apply.

PERPENDICULAR BUCKLE

This damage case is not being used in the comparison because the Angled Buckle damage scenario that encompasses the same difficulties but is also more complex.

ANGLED STEP

This damage case is not being used in the comparison because the Angled Step Non-Parallel damage scenario is a more complex composite of this and the Perpendicular Step Non-Parallel.

PERPENDICULAR STEP NON-PARALLEL

This damage case is not being used in the comparison because the Angled Step Non-Parallel damage scenario is a more complex composite of this and the Angled Step.

ANGLED BUCKLE

Wheel Tracks & Trailer – The easiest way to use the Wheel Track and Trailer repair structure would be to wheel the trailer right up to the buckle, with as much of the driving surface directly over the damage as possible. Ramps could then be put in place on both sides the driving surface essentially forming a bridge over the road buckle. If the buckle crossed the road at such an extreme angle that the ramps leading down from the driving surface could not reach the undamaged road on the other side, two Wheel Track and Trailer repair structures might have to be used. With a repair structure positioned on either side of the buckle, the ramps normally used to connect the driving surface to the ground would be used to bridge between the two driving surfaces. This configuration would allow vehicles to drive up one set of ramps to the first driving surface, cross the ramps now connecting to the second driving surface and drive down the last set of ramps to the road on the other side. The main difficulty with this setup would be getting one Wheel Track and Trailer repair structure to the other side of the buckled section of road. This might be done by using the first repair structure to partially cover as much of the road damage as possible while the second repair structure is pushed across or pulled with a winch and pulley system past the remaining damage. Unless the second Wheel Track and Trailer could be arranged to be brought to the damage from the opposite side of the buckle, something that would make the repair process much easier but cannot be relied upon, using two repair structures and getting one across the buckle could be a cumbersome task.

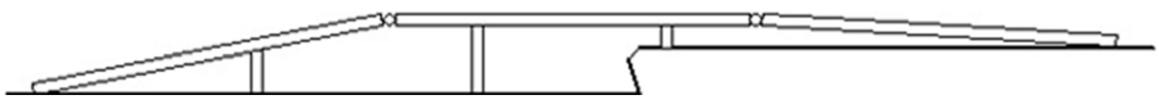


Figure 54 Single Repair Structure Setup Over a Buckle

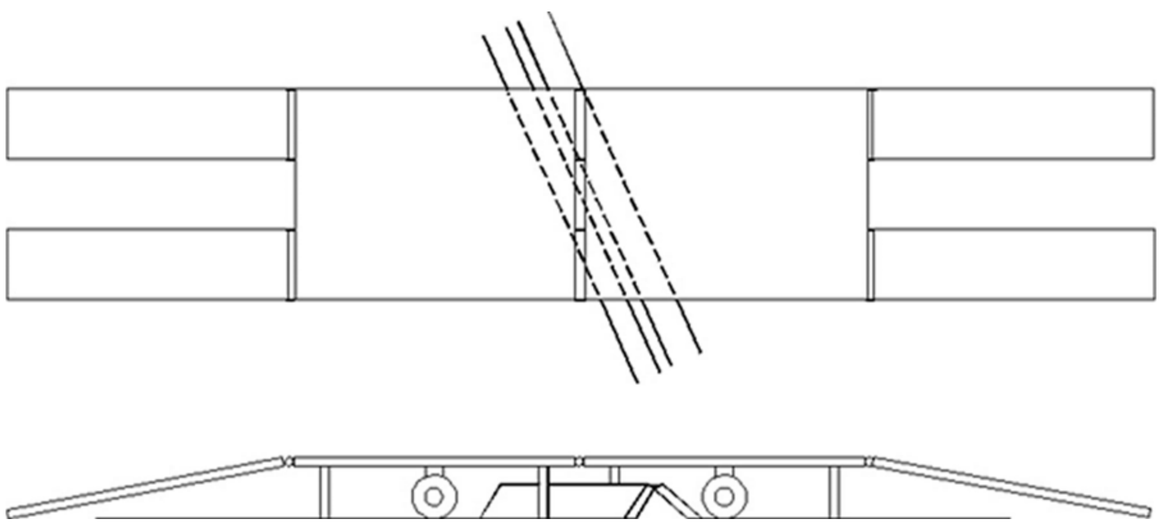


Figure 55 Dual Repair Structure Setup Over an Angled Buckle

Plate & Trailer – The only real difference in using a Plate and Trailer combination for this type of repair is that the plate most likely has to be rotated to correctly orientate the wider 3.7 m [12 ft] dimension to the traffic. This generally takes place after the repair structure has reached the location of the damage but before the deployment has begun. If the buckled section of road crossed the lane at a sharp angle, rotating the wheels and axle of the trailer might allow the repair structure to get in close enough to the damage that a single repair structure could complete the repair where the Wheel Track and Trailer combination had to use two repair structures because of its fixed axles.

Wheel Tracks & Post/Pillar/Pier – A Post/Pillar/Pier support system with a driving surface, Wheel Tracks in this case, allows for several ways to repair a bucked section of road. The severity of the road buckle would be the determining factor in which repair configuration to use. A buckled section that crosses the road fairly perpendicular to the direction of traffic could probably most easily be repaired using two Wheel Track driving surfaces. The two driving surfaces would be arranged so that they each would have one edge on the undamaged road, one on each side of the uplifted buckle zone. They would be placed angling up, meeting in the middle, in a drawbridge like configuration. The Post/Pillar/Pier supports would be used to hold the driving surface in the angled position. This would work fine as long as the buckle was not too high, allowing the driving surfaces to be set at shallow enough slopes to prevent crossing vehicles from high centering on the ridge in the middle.

Figure 56 Angled Driving Surfaces Over a Buckle

Placing the Wheel Tracks in the final angled position lends itself to the process of holding the position of the driving surface while the supports are attached. Attaching the supports before deploying the Wheel Track might complicate the positioning process. Attaching the supports after the plate had been placed on the ground and using the supports to move the driving surface into the angled position is less desirable. Using the adjustable supports for this alignment process could create difficulties with trying to get the two driving surfaces to meet in the middle at the high point.

For road buckling damage that is not too severe, another way to use the Wheel Track and Post/Pillar/Pier support is to set up a single driving surface level and centered over the buckle with ramps or additional Wheel Track driving surfaces leading up one side and down the other. This use of three Wheel Tracks driving surfaces would only be necessary in a design not intended to be used with ramps, or if no ramps were available.

Figure 57 Level Driving Surface Over a Buckle

This type of setup would also lend itself to a method of attaching the Post/Pillar/Pier supports where the Wheel Track is held in position while the support attachment and adjustment takes place. Again placing the driving surface on the ground and using the supports to raise and level it would present problems because the location of the Wheel Tracks is directly above the buckled road section. The Post/Pillar/Pier supports could also be attached before the driving surface was moved into position, but depending on how the Wheel Tracks are stored and unloaded this could make the repair structures a bit more unwieldy.

Lastly, two Wheel Track driving surface could be set up over the damage, with ramps leading up to the first driving surface, bridging between them and leading down from the second driving surface. This setup would be used in a case where a single Wheel Track and the accompanying ramps did not reach far enough to completely cross the buckled section of road. With any of the repair configurations, if the driving surfaces were being deployed with a crane or boom arm, there would not be much trouble in placing them on the far side of the buckling damage.

Plate & Post/Pillar/Pier – A Plate and Post/Pillar/Pier repair structure would be used in the same ways as a Wheel Track and Post/Pillar/Pier combination. One of the advantages that a Plate driving surface has is that vehicles can approach and cross it from any direction. This advantage is taken away when using ramps with the Plate because the ramps are basically wheel tracks and will force vehicles to approach them from straight on. This is not really an issue when the repair structure can easily be placed in line with the natural direction of traffic, but becomes more important when attempting to align the repair structure to damage that crosses the road at an acute angle.

ANGLED STEP NON-PARALLEL

Wheel Tracks & Trailer – This damage scenario is considered to be the most difficult to repair because it can involve many non-orthogonal angles, creating problems with repair structure stability and clean mating edges where the road and repair structure driving surfaces contact. The idea for using the Wheel Track and Trailer combination for this repair is to simply position the trailer as close to the step as possible, hopefully getting part of the Wheel Track above the upper level of the step, and to then use ramps to deal with the non-level ground. If the step is taller than the Wheel Track, ramps will need to be used to reach from the driving surface up to the upper level as well as deal with the skewed ground. A case like this, with the ramps reaching up to the upper level, might require ramps of different lengths, because one edge of the step could be much closer than the other, in addition to being at a different height.

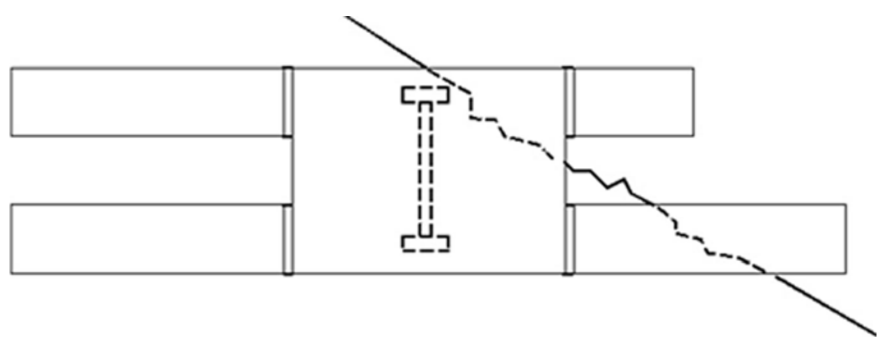


Figure 58 Top View of Plate and Trailer at an Angled Step

If the step crosses the road at too sharp of an angle to position the repair structure perpendicular to it, the option is then to effectively lengthen the reach of the repair structure so it can span all the way across the angled step. This can be done in some cases by using multiple repair structures or by adding on additional components, such as ramps. In this case where the step crosses the road at a sharp angle, having the driving surface permanently attached to a trailer seems like a disadvantage, making it difficult to position the repair structure close to the step. This is because the wheel on one side of the trailer may contact the step, allowing only a small corner of the Wheel Track driving surface to reach the upper level. Using ramps to connect the driving surface to the upper level could help solve this problem but in some cases could still be insufficient. Additionally, if one of the road surfaces was canted at an angle, the locations where the ramps contact to road would not come together with the entire width of the ramp meeting flush with the road. This would result in only a corner of the ramp being in contact with the road and would present problems by creating a large lip that crossing vehicles would have to negotiate. Also, the loading from the passing vehicles would initiate a twisting in the ramps because of the partially free bottom edge. This is a problem that could be addressed my having some sort of floating end or rotating attachment on the ramps, specifically designed to deal with sloping surfaces. Since the repair setup requires that the repair structure be positioned on the lower side of the step reaching up to the upper level, the difficulty with getting the structure down when approaching the damage from the upper level will need to be addressed.

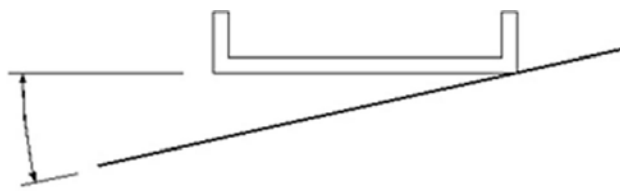


Figure 59 Ramp and Canted Road Surface Interaction

Plate & Trailer – The Plate and Trailer combination will be used in much the same way for the repair, being setup on the lower portion of the step with the driving surface and ramps used to reach the upper level. The Plate and Trailer setup does have an advantage if designed with a pivoting deck. A pivoting deck can be used to get both of the trailer's wheels right up to the step, even if the step crosses the road at a sharp angle. With the wheels up against the step, the Plate can be rotated to the correct orientation with respect to the direction of traffic. This will allow the Plate driving surface to be positioned more directly over the step than the Wheel Track driving surface without the rotation ability.

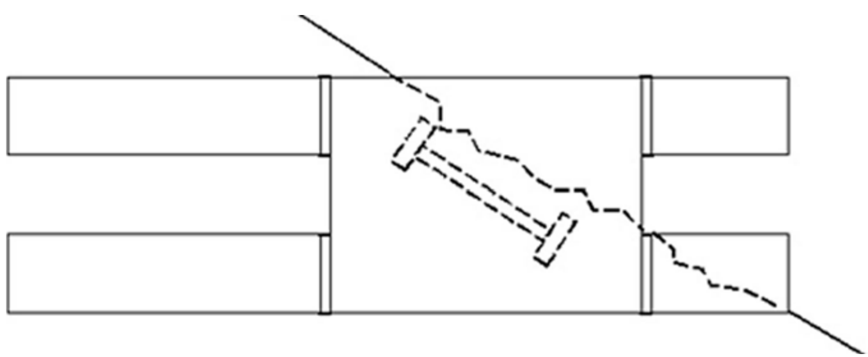


Figure 60 Top View of Rotating Axle and Angled Step

Wheel Tracks & Post/Pillar/Pier – The Wheel Tracks and Post/Pillar/Pier could be used in a few different ways, all of which involve the use of multiple driving surfaces and or additional add-ons to the repair structure, like ramps. The most basic way to use the Wheel Track and Post/Pillar/Pier is to set up the driving surface level, above or before the edge of the step. With the driving surface before the step, it should be set up high enough that if extended straight forward toward the step (along the direction traffic will follow), it will just clear the step. Another way to say this is it should be set up higher than the portions of the upper level that are in line with the direction of repair. Having it higher allows the ramps to slope down from the driving surface to reach the upper level of the step, simplifying their use and interface with uneven surfaces. Ramps will also be necessary leading up to the driving surface from the lower level. If the driving surface cannot be placed high enough to be above the upper step, it should be placed significantly back from the step so that the ramps leading up, when extended, come just to the edge of the step.

Figure 61 Repair Structure with Ramps Sloping down to Upper Surface

Figure 62 Repair Structure Ramps Reaching Up to Upper Surface

When a driving surface is lower than a step that crosses the road at a sharp angle, a shorter length ramp may be required to reach the close portion of the upper level, in order to prevent the ramp from sticking up into the air. An option other than moving the ramp back away from the step or using ramps of different lengths, is to use two driving surfaces, positioned level, one on the upper side of the step and the other on the lower side. A third driving surface or a set of ramps would be used to connect the two level driving surfaces. This configuration would allow the other ramps that connect the driving surfaces to the uneven road, to slope down from their respective driving surface, eliminating the tricky interaction of having the ramps sloping up to the edge of the step.

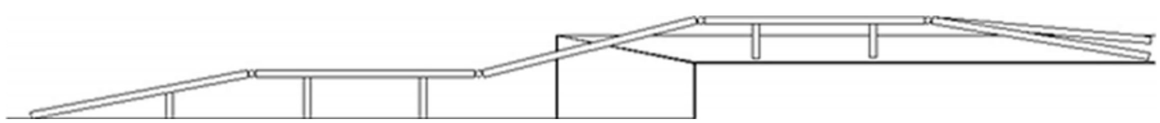


Figure 63 Multi-Repair Structure Setup on Angled and Canted Upper Surface

Any of these different repair structure configurations will rely on the extensive use of the Post/Pillar/Pier supports and ramps. When connecting multiple repair units together with ramps to create a larger structure it is essential that all of the units be correctly lined up. Because of this, placing the driving surface on the ground, which most likely will be canted and uneven, before attaching the supports and then using the supports to adjust the height seems like it would not produce the required accuracy. For this reason it makes more sense to attach the supports prior to deployment or preferably to use some external method such as a crane or boom arm to hold the driving surface in the correct position while the supports are attached and adjusted.

Plate & Post/Pillar/Pier – Combining a Plate driving surface and with Post/Pillar/Pier supports will produce a repair structure that is used in the same manner for this type of repair as the Wheel Track and Post/Pillar/Pier pairing.

Deployment Selection

The damage repair scenario descriptions do a good job of bringing to light some observations about the repair structures. They are helpful in defining critical, problem, or undefined areas of each structure concept. The following list summarizes the important ideas useful in making a decision on a final conceptual design for the repair structure, as well as some clues about what types of deployment and transportation options might work the best.

- Any of the repair structure combinations can be used successfully to repair on any of the damage cases. To complete many of the repairs requires setup configurations that make extensive use of ramps and additional supports.
- Ramps are especially helpful when dealing with uneven (non-level) surfaces or angled cracks (places with two different distances to reach); otherwise a Plate would work just fine.
- In some cases, specialty ramps or special attachments for the ramps may be necessary so the ramps can rest securely on canted surfaces.
- Repair structures are setup on the lower side of steps, unless there is a need for a second repair structure on the upper side to provide a level surface where ramps from the first repair structure can be attached. In such a case, there is still a repair structure on the lower side of the step, in addition to the one on the upper level.
- Generally, it is easier to have the repair structure higher than the damage. This is true even when the structure is setup on the lower side of a step. This is because positioning the ramps is easier when the they are sloping down from the driving surface to the road, rather than rising up to meet the road above the driving surface.
- Attaching supports to driving surfaces can be done at any time during the deployment, but for ease of positioning it is best to do it while the driving surface is held in its final position. One of the easiest ways to hold a driving surface in place is with a crane or boom arm. This allows the final position of the driving surface to be set without having to worry about height adjustments with the supports.
- Cranes and boom arms also have the advantage of being able to reach across buckled road sections and up or down vertical steps in the road.
- Positioning a Post/Pillar/Pier type repair structure using a crane can seem more straightforward than using a Trailer unit because a Trailer unit will often require some creativity in the deployment procedure in order to position all of the structures. This can involve removing some of the ramps in order to help get the trailer into the proper position.
- A trailer is by far the easiest way to transport and deploy a repair structure for simple repairs, but as a support structure it has some limitations. Approaching a step from the upper side, placing a structure on the far side of an uplifted buckle in the road, getting the repair structure positioned in the middle of a broken road surfaces, and getting the driving surface close to steps crossing the road at sharp angles all present problems.

- There are ways to deal with all of the trailer unit positioning shortcomings but they are not necessarily straightforward. Some cases can be dealt with by using a winch to lower the trailer unit down a step and some other cases by using a winch and a pulley anchored on the far side to pull the trailer across. Other trailer units and the ramps come into play for getting the trailer unit over a buckle or into the middle of a broken section of road. An extendable tongue on the trailer could also be used to push the trailer unit into position. Having a driving surface that rotates independently from the axle and wheels can allow the trailer unit to get closer to, and more centered over damage features that cross the road at sharp angles.
- A Pivoting deck on the Plate and adjustable width for the Wheel Track driving surfaces will account for the repair structure towing width when used with the Trailer.
- For simple cracks in the road, leaving behind an entire trailer setup for the repair seems excessive. Using the Wheel Tracks or Plates alone seems better. One solution is to use a detachable driving surface that could be left in place when a simple repair is all that is needed. Along the same line of thinking, the ramps alone, that all of the repair structures rely on, could be put down for small cracks.
- Many of the repairs require the use of multiple units, meaning that multiple trailer repair structures would need to be towed, possibly by either stacking them one on top of each other or linking them like a train.
- The trailer relies on the use of vertical supports for stability, making it not so different from the ideas that use a driving surface with Post/Pillar/Pier.
- The Plate driving surface does not need to be aligned with the direction of traffic as accurately as the Wheel Track, but when the Plate is elevated off the ground and using ramps, this advantage is negated.
- Integrated support and adjustment systems are very important to deployment procedures that do not rely on an external method for height positioning, i.e., cranes or external jacks. When using an external method to set the height and position of a driving surface, the support size or length only needs to be selected once.

Since each of the four repair structures can be used to repair any of the damage scenarios, the decision then came down to which repair structure would be the most versatile, the easiest in the majority of the situations and the most adaptable. At this point the decision has been made to settle on a design concept based on a Trailer support structure. After thinking through some of the detailed design issues of the trailer, it became clear, that although there are some circumstances when a Post/Pillar/Pier support with a Plate or Wheel Track would have the more straightforward deployment procedure, a Trailer structure can be deployed and in many other cases is the simpler repair method.

One advantage that the Wheel Track or Plate has is the large number of units that can be transported due to their small storage space requirements. The downside is that to transport these repair structures, a specially designed delivery unit and additional equipment are necessary; this would be something like a simple flatbed trailer with a rack to hold the driving surfaces, boom arm to lower and hold them in position while the supports are attached. Although this system would allow for easier placement of the repair structure in difficult to reach places, it still requires a specialized trailer unit, possibly a power source for the boom arm or an additional person to operate it, or more training and coordination to use. The last part, more training may be the most negative part. Since it is not likely that these repair structures will get used very often, the less specific the skill required to deploy them, the better. The trailer system could be transported with a few of them riding piggyback on the ones below, enough to make a couple of repairs before returning to the storage yard for more. This may not allow as many repair structures to be transported as the Post/Pillar/Pier and driving surfaces on a special trailer, but it can carry enough to make initial repairs before going back for more.

At their essence, all four of the repair structures are basically the same. They each have a driving surface and a support structure that features a vertical support of some type. What sets the Trailer system apart is that it has a built in transportation system, but is modular enough to function like a lone set of Wheel Tracks, if necessary, by removing the ramps and using them alone. Therefore, the Trailer and driving surface, which can complete all of the repairs, has a transportation and deployment advantage over a Post/Pillar/Pier repair structure that requires a crane or boom arm.

For the type of driving surface, it is very likely that the Wheel Tracks have a structural advantage over the Plates because of the side flanges. In addition, the flanges provide a certain amount of safety by helping to prevent drivers from straying off of the wheel track. Some modeling will be done to determine which driving surface, Plate or Wheel Track, is in fact a better design structurally. Besides the structural aspects, which could include less weight through a more efficient use of material, the Wheel Tracks are more space efficient because they can include a feature that allows them to slide together for transportation.

Summary

This chapter began with the goals of the repair vehicle and equipment being established by the design considerations. This led into discussion of the main function to be performed by the repair equipment and the establishing of functional groups for the conceptual design. With these functional groups in mind, many ideas were generated on how to accomplish the specific functions, so many in fact that combination of all the ideas in the morphological chart had 64.8 million possible combinations. From here, logical elimination, selection matrices, idea sketching, and damage repair scenarios have narrowed the design concept down to a simple and efficient repair structure that combines its own transportation and deployment solutions into its design.

The conclusion was that a repair structure consisting of a Trailer support structure and a Wheel Track driving surface could, along with the help of additional supports and ramps, effectively complete all the repair types, from simple cracks to complex vertical offsets with canted road surfaces. The Trailer support structure was chosen because of its ease of transportation and versatility. For many of the repair cases, wheeling the trailer up to the damage is the easiest way to complete a repair. For more complicated cases, additional ramps and multiple units can be connected. A trailer support structure takes care of the deployment and transportation, eliminating the need to design a costly specialized trailer or vehicle for deploying the repair structures. Additionally, because the repair structures are themselves trailers, any Caltrans vehicle with a towing hitch can take them into the field, allowing for multiple repairs to take place in different areas at one time.

Chapter 5. Design Summary and Recommendations

Previous chapters have followed the development of a concept design for the rapid repair of earthquake damaged roads, starting from an investigation of the current methods of dealing with road damage, a look at the types of earthquake road damage from previous earthquakes, establishing design goals through idea generation, and concept selection. Through this process, a conceptual design was selected featuring a repair structure in the form of a trailer, facilitating easy transportation to the site of the damage. The following sections in this chapter discuss some of the issues concerning the design of the repair structure. These include geometry, size and strength considerations. Also discussed are areas of the concept requiring further detailed design. This chapter also includes a brief review of the design process, a discussion on the intended use, and finally some suggestions of areas for further investigation.

Geometry Considerations

With the concept for the repair structure chosen at this point, the next steps involve working out details concerning the geometry and how the repair structure will interact with the vehicles using it. The following sections describe some of the issues considered in choosing some of the basic dimensions of the repair structure. Of main concern were the dimensions associated with the width and spacing of the wheel tracks, as these dimensions are important in providing ample driving surface area for a wide range of vehicles. These sections also deal with ensuring that the wheel tracks and repair structure are designed and setup to adequately accommodate all necessary vehicles. Some of the issues addressed include slope changes that might cause high centering, and the flange sizing that could also cause clearance problems.

It should be noted that although some sizing and dimensioning of portions of the repair structure take place in the following sections, not all of the possible factors have yet been considered in this initial conceptual portion of the design. For instance with the wheel tracks, the dimensions have been selected to accommodate vehicle dimensions, which is only one factor to consider in the complete design. Detailed design of the ramps and wheel tracks will still need to take place. The ramps and wheel track driving surface basically have the same dimensions but could, and probably will be radically different in a structural sense, since they function in slightly different ways and will see different types of loads. The shape of the wheel track was chosen to be a simple channel, but additional optimization may find that other more complex shapes, including lips, hollows, ribs, and box sections might provide additional strength and rigidity.

Track and Tire Widths

The basic dimensions of the ramps and wheel tracks were sized based on geometry considerations. The general dimensions such as the internal track width and the height of the flanges were chosen based on the vehicles that the ramps and wheel tracks would be handling. Specifically, they need to accommodate vehicles ranging from small cars to large trucks, such as the tractor unit of a tractor-semi trailer. The internal width of an individual wheel track was chosen so that a set of dual rear tires having a width of approximately 0.6 m [2 ft] per set would have 0.23 m [0.75 ft] on either side of the tires as the set drove directly down the middle of the wheel track. This makes the internal width of each wheel track equal to 0.6 m [2 ft] with an additional 0.46 m [1.5 ft] (2 times 0.23 m [0.75 ft]) for a total width of 1.1 m [3.5 ft].

The width that the wheel tracks open to was chosen so that when open, each wheel track would be evenly centered under the right and left sides of the tractor unit of a tractor-semi trailer. The tractor units have an average outside width dimension of 2.4 m [8 ft], so having the deployed wheel tracks open 0.76 m to [2.5 ft] apart positions each 1.1 m [3.5 ft] wide wheel tracks directly under each side of the truck with 0.23 m [0.75 ft] of space on either side of the dual wheel sets. This makes the total width of the deployed structure 2.9 m [9.5 ft], two 1.1 m [3.5 ft] wheel tracks set 0.76 m [2.5 ft] apart.

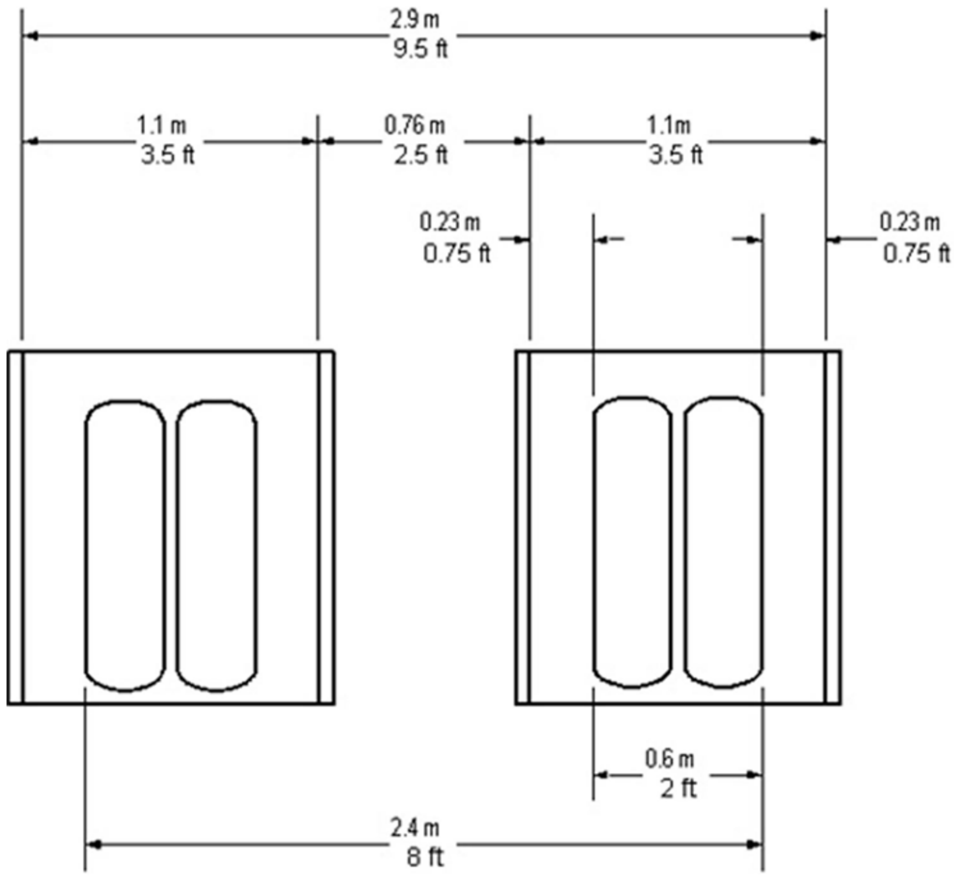


Figure 64 Wheel Track Dimensions Showing Dual Wheel Set Spacing

Also considered was that the smallest track width on cars is in the range of 1.26 m [4.15 ft]. For these small vehicles with narrow track widths, the constraining dimension is the 0.76 m [2.5 ft] space between the wheel tracks. It should be noted that the track width is not exactly equal to the inner space between the vehicle's wheels. The track is measured from the centerline of right wheel to the centerline of left wheel, so the inner space is equal to the track width minus a wheel width. For a vehicle with small track width of 1.26 m [4.15 ft] and a conservatively large tire width of 200 mm [7.9 in], the inner space is equal to 1.1 m [3.5 ft]. On the repair structure with a 0.76 m [2.5 ft] space between the driving surfaces this leaves 300 mm [1 ft] of space, or if the vehicle was driven evenly over the space between the wheel tracks, 150 mm [0.5 ft] of space between the inside of each tire and the inner edges of the wheel tracks.

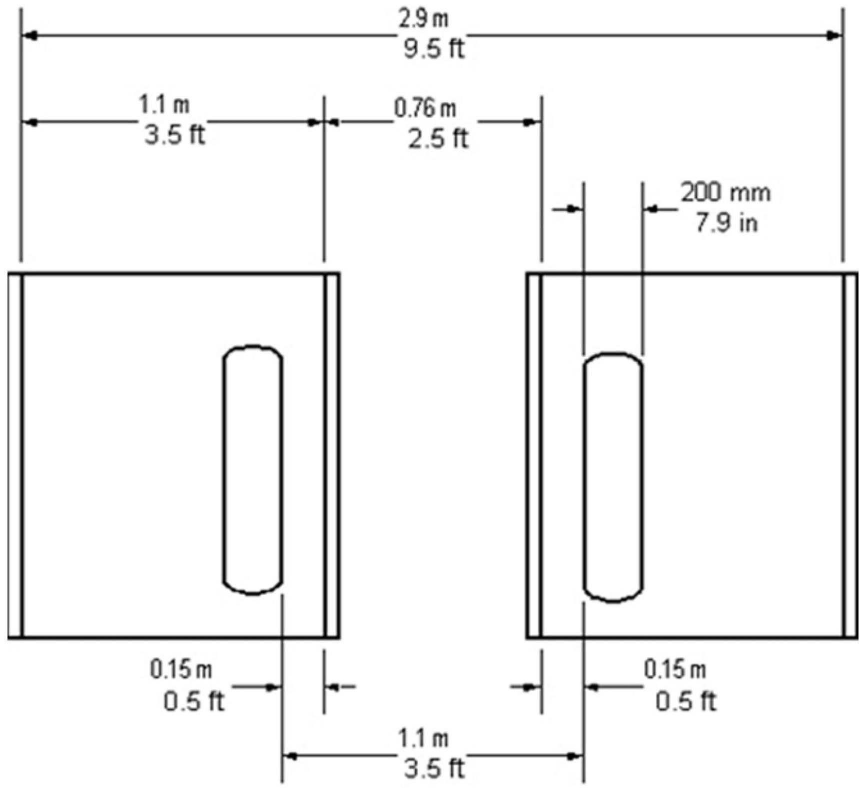


Figure 65 Wheel Track Showing Small Car Spacing

Flange Sizing

The vertical flanges on the sides of the ramp and wheel track driving surfaces provide two attractive functions. One thing the flanges do is help guide vehicles by providing a physical barrier to drive over, keeping the vehicles on the repair structure driving surface. The second thing the flanges do is provide stiffness to the ramps and driving surface. The flanges perform both of these functions better as their height is increased. Of course there is a limit to the size of the flanges, at some point increasing the height of the flanges will no longer continue to provide the same amount of structural gain, but more practically the height will be limited by the clearance of small cars. Also, the design of the repair structure includes ramps that fold back onto the main platform wheel tracks. Extremely large flanges would interfere with and complicate this function as well as the design of the hinges. The height of the wheel track flanges were selected to be 10.2 cm [4 in], a size that is high enough to provide some wheel guidance, and short enough to not introduce clearance problems for small cars. This chosen flange height was mainly selected on the basis of vehicle clearance and does not necessarily represent the optimum design for the ramps and wheel tracks.

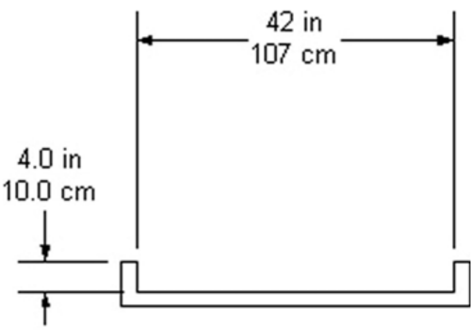


Figure 66 Wheel Track Cross Section Showing Track Width and Flange Size

Ramp Slopes and Structure Height

The general idea is that the slope the ramps or repair structure can be inclined at is limited, with the maximum slope chosen to coincide with the slope limits placed on driveways by municipalities. Driveways are typically limited to 15% to 20% slope. A 2.4 m [8 ft] ramp can reach a height of 0.46 m [1.5 ft] when inclined with a slope of about 19% or an angle of 10.8°. The height that can be reached is then determined by the slope and length of the ramp. With the maximum slope fixed, the height then depends on the length of the ramp and shortening the ramp length will accordingly lower the height the repair structure can reach.

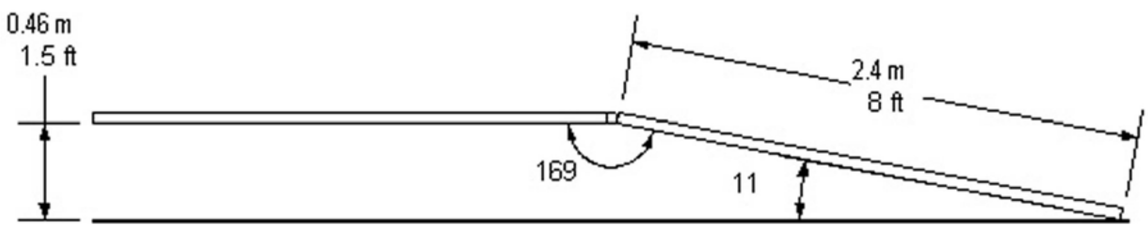


Figure 67 Ramp Angle and Structure Height

A consideration is that vehicles with low clearance may have high centering problems at places where two different slopes meet, such as where the inclined ramps meet the level wheel track driving surface. A calculation shows that a ramp inclined at 10.8° meeting a level wheel track driving surface will result in an angle of 169.2°. For example, a vehicle with a wheel base of 237 cm [93.3 in] and a ground clearance of 12 cm [4.7 in] can clear a slope change with an angle of 168.5°, but anything more abrupt (a sharper smaller angle) would cause the vehicle to high center. The vehicle in this example would be able to cross the 169.2° angle of the repair structure without incident.

This is important because it is ideal to have the ramps coming off of the repair structure leading downwards. This orientation makes the interface between the ramps and the road surface much easier to deal with than when a set of ramps are reaching up to a road surface that is above the level of the repair structure. The temptation would be to have the repair structure rise 0.46 m [1.5 ft] with the first set of ramps, and have the main driving surface also inclined and rise another 0.46 m [1.5 ft] for a total height of 0.9 m [3 ft] before having the last set of ramps sloping down. A problem could arise if the last set of ramps, although still under the 19% [10.8°] slope limit, sloped down too sharply and created a high centering situation at the last joint, with an angle much sharper than 169.2°. The following illustrates a case where the ramps and structure are all set at the slope limit, but a high center condition is created at the top. The best method when setting up the repair structure is to only have the repair structure rise just high enough that the last set of ramps is slightly angling downwards, avoiding angles sharper than 169.2 °.

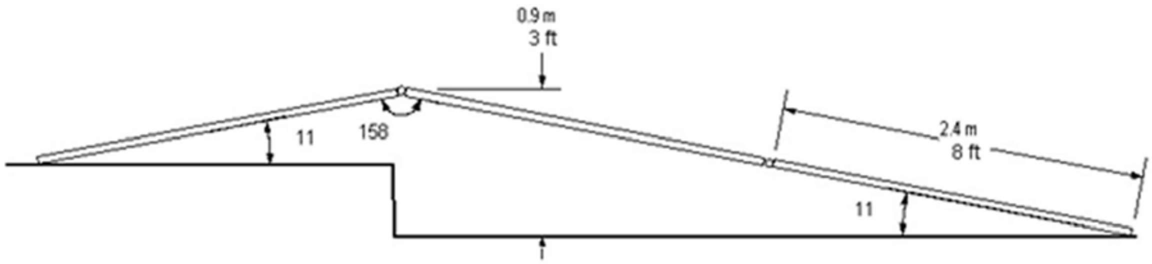


Figure 68 Ramps Inclined at Limit but High Centering Condition Exits at Top

Off Tracking

Off tracking refers to the fact that as a vehicle goes through a steady-state turn, the rear wheels do not follow the same path as the front wheels. The radius of the curve occupied by a rear wheel will be smaller than the radius of the curve occupied by the front wheel on the same side of the vehicle. This happens both with the wheels on the inside and outside of the vehicle and the difference between the two radii for the front and rear is termed the off tracking. Off tracking comes into play in situations where a vehicle is traveling straight down a road and needs make a turn in order to drive onto the repair structure ramps, which are not placed in line with the direction of traffic.

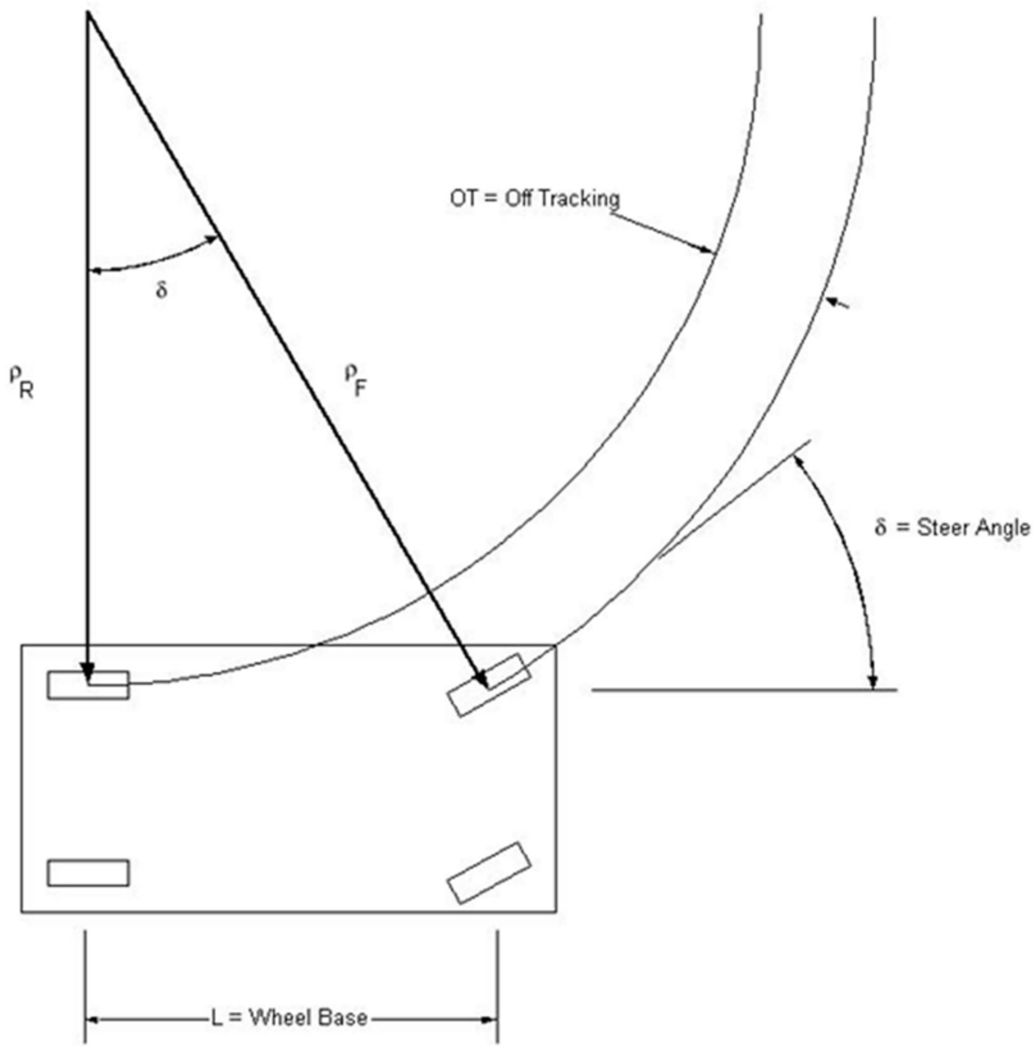


Figure 69 Off Tracking Diagram

In a situation where a vehicle is making a turn to enter onto the ramps, off tracking will occur and the width of the ramp or wheel track and the amount of off tracking becomes important. If the off tracking is too great, the rear wheels of the vehicle are in danger of missing the ramp. The amount the rear wheels of a vehicle can off track from the front wheels and still allow the vehicle to safely enter onto the ramps depends on the track and tire widths of the vehicle, and how those dimensions correspond to the wheel tracks and their spacing. Different vehicles will have different amounts of available off tracking for a particular repair structure. Another way to think about the available off tracking is if the vehicle is all the way to one side of the wheel track, the available off tracking is how far it can move unrestricted in the other direction. The width of an individual wheel track, or the gap in between the two wheel tracks, or the outer dimensions of the repair structure might restrict the vehicles movement to the other side.

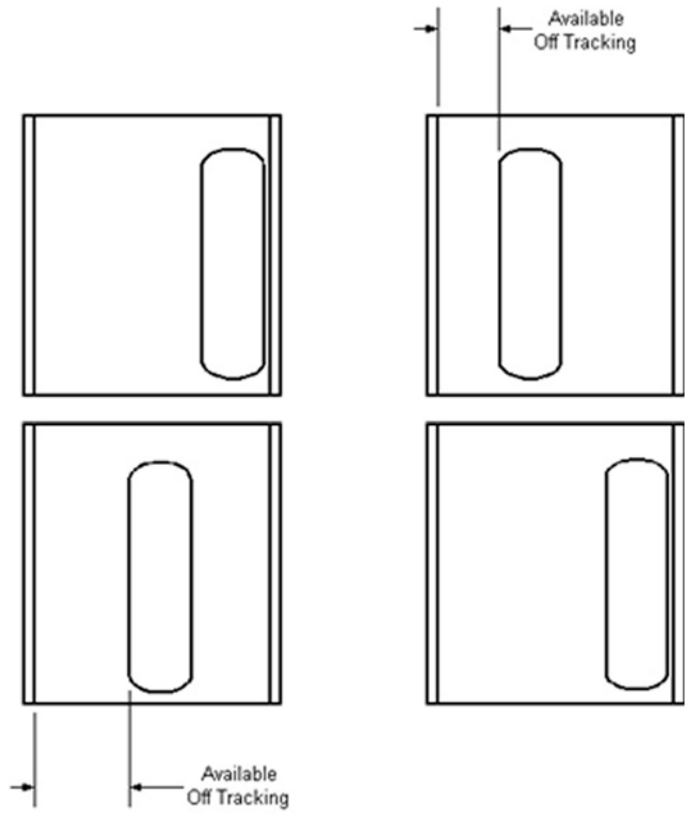


Figure 70 Examples of Two Different Amounts of Available Off Tracking on the Ramps

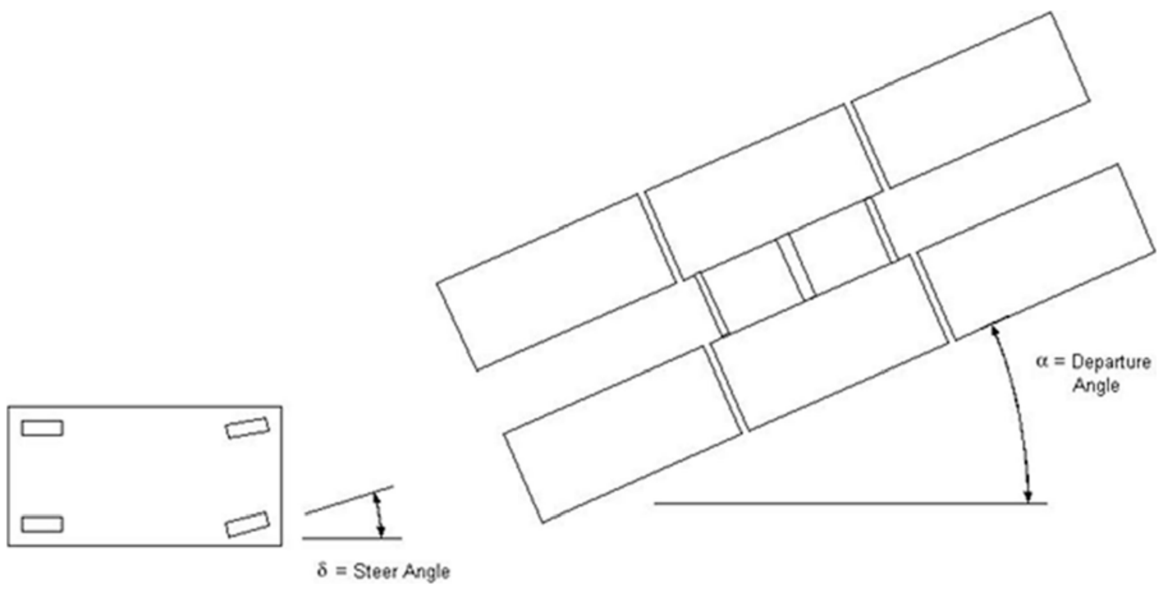


Figure 71 Structure Departure Angle Off Tracking Situation

The angle away from the normal direction of traffic that the repair structure is positioned is termed the departure angle, and the greater the departure angle the more a vehicle will have to turn to enter onto the repair structure ramps. Sharper turns mean more off tracking, so a relation was sought to help assess maximum allowable departure angles. The formulation is

$$\alpha = 2 \arctan (OT / L) \tag{7}$$

where α is the departure angle, OT is the off tracking and L is the vehicle wheel base. Eqn 7 is based on the assumptions of steady-state turning, a constant steering angle throughout the turn, and the turn ending with the front wheels tangent to outside edge of available wheel track space, which in turn means that the steering angle throughout the turn is the same as the departure angle; see Appendix 1 for the derivation. This relation allows for the calculation of a departure angle based on a vehicle's wheelbase and the available off tracking, which is based on the track and tire width interface with the wheel track width and spacing. The assumptions used make this relation conservative, as this does not represent the best method for entering onto the repair structure while turning.

Driving Surface Analysis

This brief and simplified comparison was done to verify the strength and weight benefits of the wheel track design over the flat plate design. There are also other reasons besides strength (being verified in this comparison) why the wheel track was considered to be superior, including increased maneuverability due to smaller storage space, and safety from the vertical flanges acting as guides to ensure that the vehicles remain on the driving surface. Looking at the stresses and cross sectional areas involved in the calculations it can be seen that additional detailed design work is necessary to select the appropriate material and final design for the wheel track, perfecting the shape of the wheel track and optimizing the thicknesses for the load.

The comparison was done with the two basic shaped driving surfaces of the same volume, and since the analysis was done using the same material, the same weight. The bending stresses due to a given load were calculated for the two differently shaped driving surfaces and the results compared. This analysis was done for a range of wheel track thickness from 13 mm to 32 mm [0.50 in to 1.25 in], with the plate thickness varying accordingly to maintain the same cross sectional area for the two driving surface shapes. The calculations have shown that in the thickness range, the wheel track is able to support 1.5 to 3 times more load for a given amount of material. Conversely, a wheel track design could support the same load at the same stress level and use considerably less material, and thereby be lighter. Again these are simple bending stress calculations and do not account for any stress concentrations, cross section deformation, or out of plane loading, but have been employed to simply show the general trend in the increased strength of the wheel track design.

Ramp Length Discussion

There is some concern that the 2.4 m [8 ft] long ramps would need to be so massive to span the full distance that they would weigh too much to be easily deployed by hand, rendering them essentially useless for the intended scope of the repair structure. Some initial calculations show that this may be the case, but without a complete detailed design, it is difficult to make a full assessment. There are however some alternative ideas to using 2.4 m [8 ft] long ramps, including shorter ramps (which might reduce the overall height the repair structure can reach), supports in the middle of the ramps, or two section ramps that can be connected in the middle at a support when the extra length is necessary. This brings up the interesting point that, while a 2.4 m [8 ft] ramp would help reach a greater height, a ramp of that length may not always be necessary on both sides of the repair structure. There may be times when a 1.8 m [6 ft] length or two 1.2 m [4 ft] lengths would work better.

Conceptual Design Details

Although at this point the basic architecture of the repair structure design has been decided, there are still some areas that require additional attention. Details of the design such as the structure of the trailer, tow bar, hitch, axle, the adjustable width wheel tracks, the vertical supports, and the ramps and hinges all still need to be considered. Because this is a conceptual design, these details will not be completely determined here, but some different ways of accomplishing each function will be considered, most importantly so that it is apparent that the functions can be accomplished. Again all of these following sections are appropriate for further investigation, as these are more suggestions than final details, as the final design details are not the main thrust of this report.

Trailer Frame Construction

Most likely the frame for the trailer will consist of a fixed rectangular structure, a bit smaller than the width and length of the trailer when it is collapsed in transportation mode. The frame will serve as the backbone to which all of the additional components are fixed. This would include the wheel track driving surfaces, the vertical supports, and the towing apparatus such as the axle and tow bar.

Wheel Track Width Adjustment

The wheel tracks, because the design requires that they have a width adjustment, need to be attached to a track or slider rail that will allow them to move in and out. Since the total deployed width of the structure is only 2.9 m [9.5 ft], the two wheel tracks only need to move 0.46 m [1.5 ft], 0.23 m [0.75 ft] each, to allow the repair structure in transportation mode to be within the 2.4 m [8 ft] vehicle width limit. The slider rails will mount to the rectangular trailer frame and allow the wheel tracks to lock into two positions, the closed transportation and open deployed positions.

Vertical Supports

Besides the driving surface, the vertical supports are probably one of the most important parts of the design concept. During deployment the repair structure will make copious use of supports, and their ability to support the necessary loads as well as be highly adjustable is crucial. Ideally the supports will be easy to attach to portions of the repair structure if necessary, as well as collapsible enough to not interfere with transportation and deployment if left in place.

The most likely configuration for the vertical supports will be scissor jacks that can attach at necessary points along the frame of the trailer. Since the trailer is already on wheels and up off the ground, the jacks would not be used for extensive lifting of the structure, just leveling and stabilization, so it is feasible to have the jacks operated by hand. An ideal set up involves a slip nut that would allow the jack to be quickly opened to the point where it would then begin to do the lifting. At this point the slip nut would lock down and the jack would operate in a normal fashion. Some of the drawbacks of the scissor jacks include the stability of the jacks, and the mechanism at the connection point. The connection point is an important interface that has to transfer large loads as well as serve as an easy mechanism for removing and attaching the supports as needed. Another type of jack that could be implemented into the construction of the vehicle is sort of a half-scissor jack, permanently mounted to the underside of the trailer frame. This would function in the same way, unfolding quickly until it contacted the ground, were the screw nut could then be locked in place and the jack cranked into the desired position.

Ramps and Hinges

Like the Vertical Supports from the preceding section, ramps too are integral to the design of the repair structure. In preceding sections in this chapter, like “Ramp Length Discussion” and “Ramp Slopes and Structure Height” some of the length issues have already been addressed. Strength and structural issues have already been touched upon briefly in the “Ramp Length Discussion” and “Driving Surface Analysis” sections.

The ramps connect to the main portion of the repair structure by way of hinges that also allow the ramps to be removed when not necessary or when needed on their own, without the rest of the repair structure. The hinges, while seemingly simple, are a piece of the repair structure design that should not be overlooked. As the design is now, the main hinges will have to bear large loads as vehicles pass over. The hinges will also have to allow for easy attachment and removal of the ramps, which is one of the main features of the conceptual design. Another vital area that will need to be addressed by the hinge design is how the ramps will fold up, assuring that there will be clearance for the 10.2 cm [4 in] tall flanges.

In order for the ramps to fold over but still allow room for the 10.2 cm [4 in] tall flanges, a special hinge is necessary. This can be a double hinge or a single 5 cm [2 in] high hinge. The double hinge would have one portion, the joint closest to the repair structure, only able to move 90°. The other joint, closest to the ramp, would have full range of motion. The height of the 5 cm [2 in] high hinge is necessary to provide clearance for the flanges, but would cause the hinge to stick up above the surface of the ramp and wheel track. This would create a possibility that passing vehicles could damage the hinge.

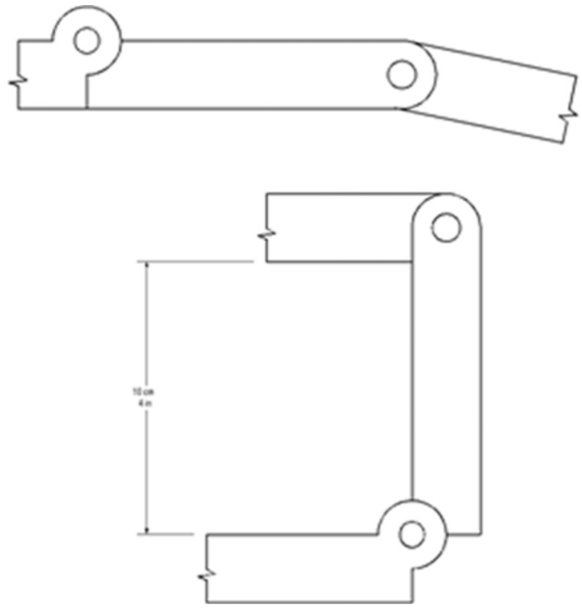


Figure 72 Double Hinge

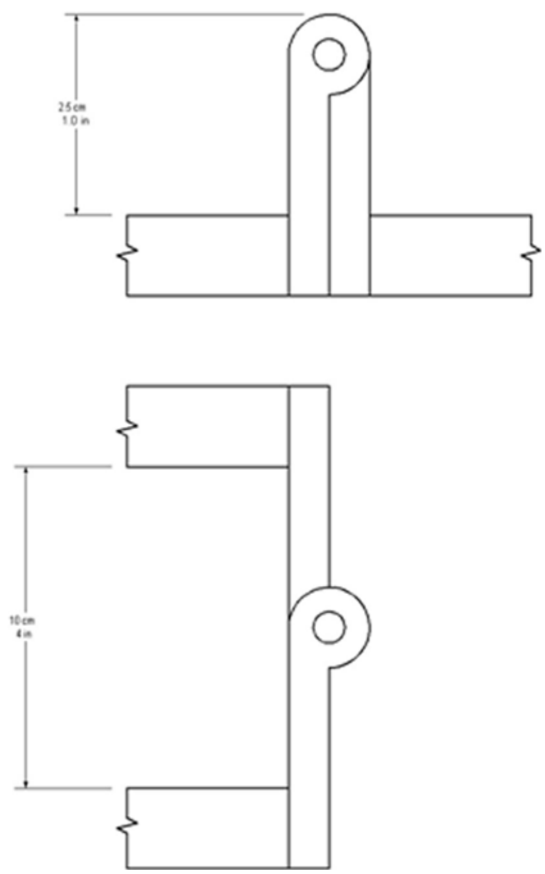


Figure 73 Tall Hinge

In order to get the ramps from both sides of the repair structure to lie flat when they are folded in, one hinge will have to be larger than the other, so that the second ramp folded over can lie on top of the first. Another possibility is to have two ramps of slightly different sizes so that they fit inside of each other. This of course means that for the ramps to fold together they must always be a pair with one slightly larger than the other. This would not be much of a problem if the ramps were permanently connected to the repair structure, but because they are removable, it introduces the possibility of a mismatch. There are ways to prevent this, like only allow the hinge on a ramp to fit in one place, but the fact is that this introduces compatibility issues that users must be aware of. Additionally the slightly narrower of the two must always be folded down first, so that larger one will fit over it. Also, if the second ramp was simply prevented from folding all the way over, identical ramps and hinges could be used on both sides of the repair structure. The repair structure would most likely be stored in this manner to facilitate easy deployment.

Design Review and Suggestions

The following sections review some of the ideas leading up to final conceptual design, provide some suggestions on how to use the repair structure and finally offer recommendations for areas of further study.

Review, Meeting the Design Considerations

This conceptual design project began with identifying the types of damage that would be targeted for possible repair, and setting some repair parameters. Among these parameters were the design goals that the concept be easily transported, effective at opening damaged roads and self-contained. This led into the consideration that to be effective, the design would need a fast response time that comes from having units placed in several locations throughout the state. Because of the high possibility of this equipment being used very infrequently, and the desire to have the equipment at many locations, the decision was made to focus on the simplest repair method requiring the least amount of new machinery.

With this in mind, the task of repairing an earthquake damaged road with some sort of structure was broken down into functional groups. These functional groups made it apparent that the driving factor of the design would be the repair structure itself, as everything else from the transportation and deployment depended almost entirely on what was being transported and deployed.

Through the idea generation and concept selection, a design featuring a repair structure based on a trailer was selected. Going with a design that was also a trailer solved many of the deployment and transportation issues and allowed for a cheaper repair structure that could be moved by any vehicle with a tow hitch, improving its versatility.

Use Suggestions

For this repair structure to be most effective, it should be stored at Caltrans equipment yards with three trailers already stacked in a piggyback fashion, as shown in the following. This way, at the moments notice of an emergency, any vehicle with a trailer hitch could hook up the bottom trailer and soon be on the way with the three repair structures in tow. At the site of the repair, depending on the number of repair structures necessary for the repair, the extra structures could be wheeled off the bottom repair structure and stashed at the side of the road, to be towed on to the next repair when the current repair was finished.

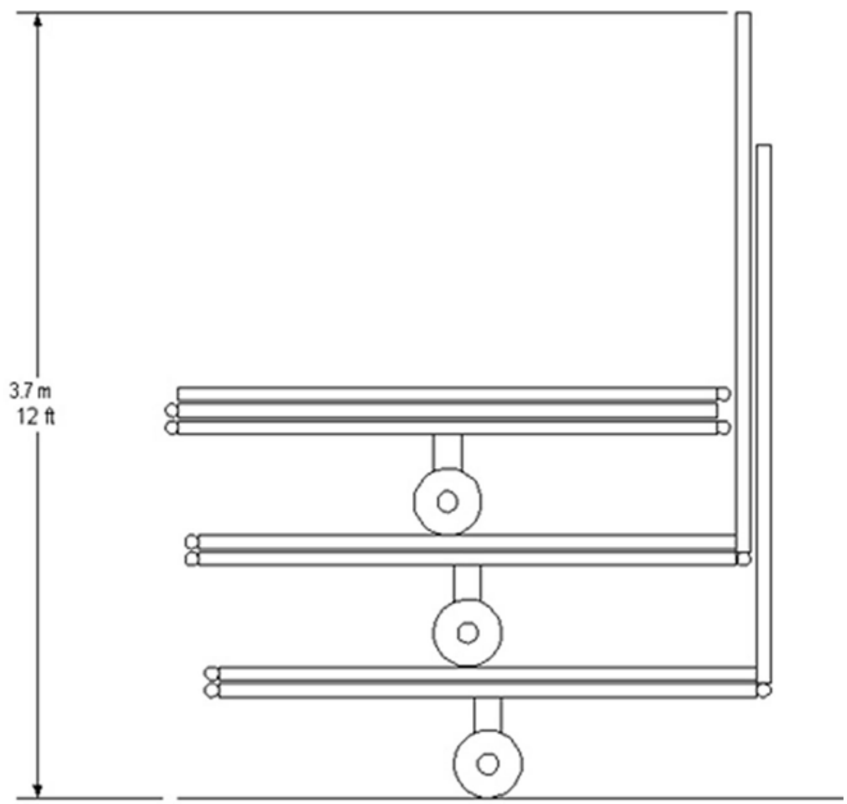


Figure 74 Three Trailer Units Stacked "Piggyback"

This design has concerned itself with repairing surface damage from earthquakes, which is limited to primarily surface faulting and liquefaction. There are many other ways a road can become closed, such as structure collapse and hazardous material release, which are far out of the scope of this piece of equipment. In some circumstances it may be best to go with an entirely different method of repair. Rather than simply trying to use a structure to cover the road damage, it may be best to utilize a road fill method to fill in the damage. Long road sections with lots of minor cracks would probably better be repaired with a road fill material rather than numerous repair structures linked together, although it could be accomplished with multiple repair structures if necessary. The repair structure can also be combined with some of the other repair ideas. For example, a mat could be placed over soft or loose soil to aid vehicles in the approach to the repair structure.

Open Issues and Recommendations

The areas of the concept that most obviously need design optimization are the ramps and wheel tracks. The ramps are more structural than the wheel tracks, which will be supported by the trailer frame, but both would benefit from a detailed structural analysis. All of the topics in the "Conceptual Design Details" section like the Trailer Frame Construction, Wheel Track Width Adjustment, Vertical Supports, Ramps and Hinges are areas needing further work. Not explicitly mentioned in the above subsections, but also still needing detailed design, are the connection and attachment points, the hitch and tow bar, and the axle frame interface. Some of these are discussed in this last chapter, but no final or detailed design has been done.

It is worth mentioning that within the concept selection there were many other good ideas, that while not selected here as the final concept, would also make worthy road repair devices. The main reason they were not selected was because of the transportation and deployment advantages present with the trailer design concept. Many of the alternate designs would have to feature a dedicated vehicle or trailer, allowing many repair structures to be carried and employing some sort of crane or boon arm for the repair structure deployment. This option would require a more skilled operator and possibly some sort of power source to operate, but would be suited to placing a large number of repair structures and in difficult to reach places.

Summary

This repair structure can play a vital role in emergency preparedness, providing a valuable function in emergency situations. In the critical hours after a disaster, this piece of equipment can facilitate the evacuation of people and the flow of repair, law enforcement and emergency vehicles. There has previously been no extensive plan developed on how to deal with road damage, as it is assessed on a case be case basis by the California Highway Patrol and Caltrans. In emergency situations where time is critical, a plan and a tool such as this repair structure can go a long way to maintaining open transportation corridors and speeding disaster recovery.

Chapter 6. Mat Structural Analysis

Theory of Plate Bending

The main intention of this chapter is to analyze the mat and its response during bending conditions. To simulate a typical Aluminum mat used in the Rapid Runway Repair, a simple model would be considered. As noted in a previous chapter, the Aluminum mat has a honeycomb sandwich structure. In this chapter, the equations will be developed for a homogenous mat, which is modeled as a plate. In the next chapter, the method employed for developing an equivalent homogenous model (e.g., homogenizing the composite structure) will be presented.

Basically the mat is proposed for conditions where the crater is filled and covered by mats to avoid foreign object damage. But it is possible that without filling the craters, the mats can be placed and can be used as a platform for the emergency traffic. Since the mat surface is assumed to be plane and not curved, it is considered to be a plate. The analysis was done on a symmetrical dimensionless plate with initial unit load, unit dimensions and later by varying the quasi-static load. The optimization of the boundary conditions was done with respect to these load conditions. A detailed study of the plates is discussed below.

In both thin plate and thick plate theories, the stress resultants are considered to be in equilibrium with the applied forces and the boundary conditions are imposed on a macroscopic scale. Plates and shells are three-dimensional solids. However, the thickness of such structures is very small compared with other dimensions. The simplest symmetric geometry of our element type is, a rectangle with equal sides, a square. A flat plate supports transverse loads by bending action. The material is homogenous and linearly elastic for which stress distribution would be evaluated upon application of load. The classical plate equation arises from a combination of four distinct subsets of plate theory: the kinematic, constitutive, force resultant, and equilibrium equations. This theory used in this report is based on the thin (Kirchhoff) plate theory. It is repeated here for completeness.

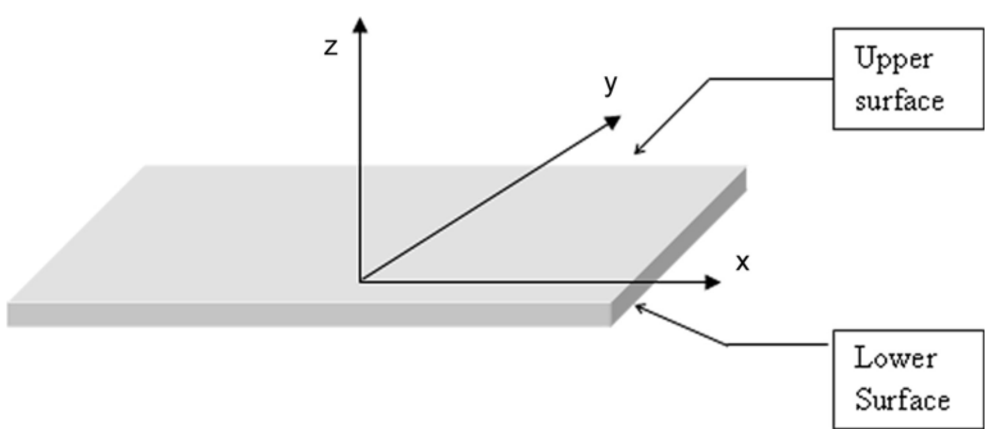


Figure 75 Coordinate definition of the plate

The Coordinate definition of the plate is shown above. Normal stresses vary linearly and are associated with bending moments along the x and y directions. Shear stress also varies linearly with z and is associated with twisting moment. Normal stresses along z are considered negligible in comparison with the normal stress along x and y and the shearing stress xy component. Transverse shear stress components yz and zx vary quadratically with z. Lateral load ‘q’ includes surface load and body force in the z – direction. For pure bending conditions, the external loads have neither components parallel to the xy plane nor normal stress components along the x and y direction and shearing stress component within the plane of the mid surface.

The bending moments and transverse shear forces for the mat are:

$$M_x = \int_{\frac{-t}{2}}^{\frac{t}{2}} \sigma_x z dz \qquad M_y = \int_{\frac{-t}{2}}^{\frac{t}{2}} \sigma_y z dz \qquad M_{xy} = \int_{\frac{-t}{2}}^{\frac{t}{2}} \sigma_{xy} z dz$$

$$Q_x = \int_{\frac{-t}{2}}^{\frac{t}{2}} \tau_{zx} dz \qquad Q_y = \int_{\frac{-t}{2}}^{\frac{t}{2}} \tau_{yz} dz \tag{6.1}$$

where M_x, M_y, M_{xy} denote the bending moments with respect to x, y axes and xy plane respectively, and Q_x, Q_y denote the shear forces in x and y axes respectively. The integrals extend over the thickness. The notation, t, denotes the thickness of the plate, σ_x is the stress along x-direction, σ_y is the stress along y-direction, σ_{xy} is the shearing stress.

The curvature /displacement equations are:

$$\kappa_x = \frac{\partial^2 w}{\partial x^2} \qquad \kappa_y = \frac{\partial^2 w}{\partial y^2} \qquad \kappa_{xy} = -2\frac{\partial^2 w}{\partial x \partial y} \tag{6.2}$$

where κ_x, κ_y denote the curvatures along the x, y axes respectively and κ_{xy} denotes the twist. w denotes the displacements along the z-direction.

Analysis of Mat Geometry

For completeness, the mat theories are presented here. A modulus – weighted reference plane is referred to and each point on the z -direction is weighted by a ratio E/E_1, where E_1 is an arbitrary reference modulus. The centroid of the plane is at a distance $\bar{z}_0$, where

$$\bar{z}_0(x, y) = \frac{1}{t^*} \int_{z_{0l}(x,y)}^{z_{0u}(x,y)} z_0 dz_0^* \tag{6.3}$$

and t^* and dz_0^* are modulus weighted variables. The modulus-weighted aspect of the mat has been shown in the following.

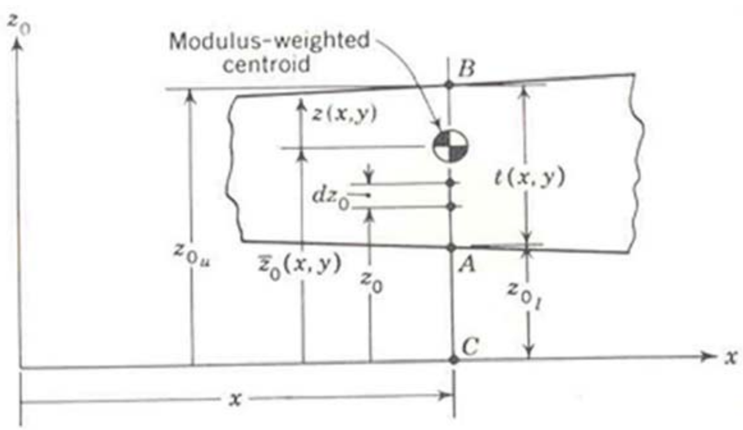


Figure 76 Modulus weighted aspect of the mat

In the analysis of Aluminum Am-2 mat structures, the plate is assumed to be homogenous, then $t^* = t$ and the reference surface is the middle surface of the plate. The non-homogenous condition was considered if the mat has a honeycomb panel sandwiched. The honeycomb panel is reduced to an equivalent E_{eq}. This concept will be discussed in detail in further chapters. Under homogenous conditions, when loaded the deformed surface has slopes $\frac{\partial w}{\partial x}, \frac{\partial w}{\partial y}$ in the x and y directions, respectively. The displacements along the x, y and z directions are considered to be u, v and w respectively and x', y', z' are the deformed reference coordinates. Accordingly, we write

$$\left(\frac{\partial w}{\partial x'}\right)_{\max,\min} = \pm\sqrt{\left(\frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2} \tag{6.4}$$

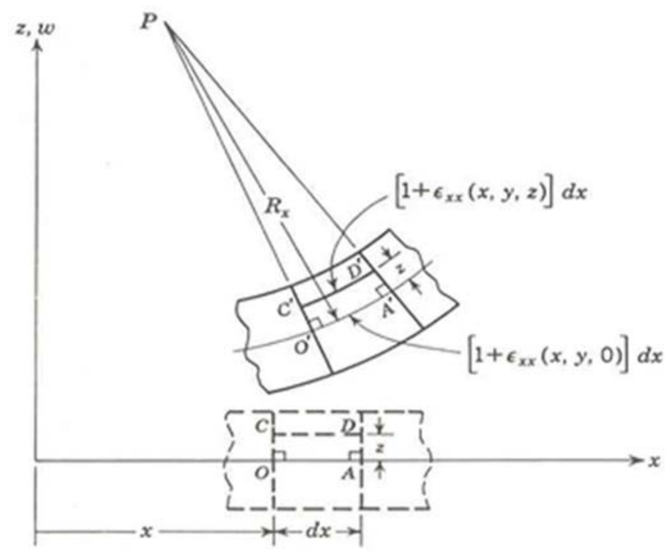


Figure 77 Curvature of the mat structure

The curvatures of the deformed plate can be considered by viewing a point O in the reference plane to O' in the deformed plane and the curvatures in x and y directions are given as,

$$\frac{1}{R_x} = \frac{\dfrac{\partial^2 w}{\partial x^2}}{\left[1+\left(\dfrac{\partial w}{\partial x}\right)^2\right]^{3/2}} \qquad \text{and} \qquad \frac{1}{R_y} = \frac{\dfrac{\partial^2 w}{\partial y^2}}{\left[1+\left(\dfrac{\partial w}{\partial y}\right)^2\right]^{3/2}} \tag{6.5}$$

where R_x , R_y are the radii of curvature in the x and y directions respectively. Figure 3.3 explains the curvature where ε_{xx} is the strain along the x-direction.

The lateral deflections $\left(\frac{\partial w}{\partial x}\right)^2$, $\left(\frac{\partial w}{\partial y}\right)^2$ are very small when compared to unity and neglected. The curvatures result in,

$$\frac{1}{R_x} = \frac{\partial^2 w}{\partial x^2} \qquad \text{and} \qquad \frac{1}{R_y} = \frac{\partial^2 w}{\partial y^2} \tag{6.6}$$

A surface is called synclastic if it has the centers of curvature lie on the same side of the plate. It is called anticlastic when the centers are placed on opposite sides.

For an arbitrary direction x_{arb}, we have

$$\frac{1}{R_{x_{arb}}} = \frac{\partial^2 w}{\partial x^2}\cos^2\alpha + \frac{\partial^2 w}{\partial y^2}\sin^2\alpha + \frac{\partial^2 w}{\partial x \partial y}\sin\alpha\cos\alpha \tag{6.7}$$

where the $\left(\frac{\partial^2 w}{\partial x \partial y}\right)$ term is the rate of change of the x direction of slope in the y direction. This term is nothing but the twist of the surface $\frac{1}{R_{xy}}$ and with respect to x_{arb} and y_{arb} axes is written as

$$\frac{1}{R_{x_{arb}y_{arb}}} = \frac{\partial}{\partial x'}\frac{\partial w}{\partial y'} = -\left(\frac{1}{R_x} - \frac{1}{R_y}\right)\sin\alpha\cos\alpha + \frac{1}{R_{xy}}\left(\cos^2\alpha - \sin^2\alpha\right) \tag{6.8}$$

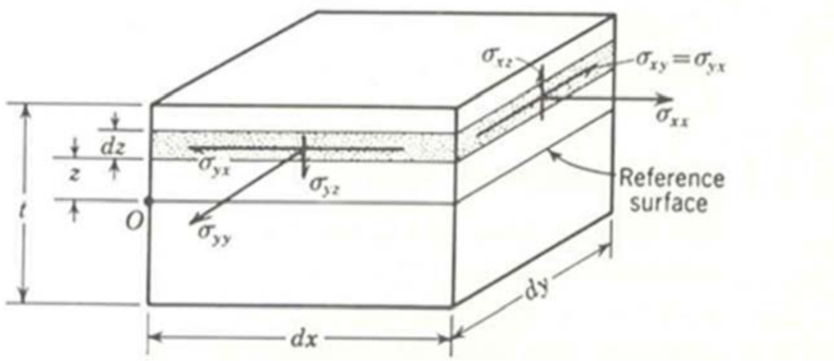


Figure 78 Stress resultants over the differential element

Since the twist is considered to be zero, a set of orthogonal principal directions exists for the plate and the curvatures have maximum and minimum values in these directions. The above figure shows the stress resultants over the differential element.

Equilibrium Conditions

Consider a loaded plate with components p_x, p_y and p_z parallel and positive in the direction of the coordinate axes shown. The stress resultants are in equilibrium with the applied loads. Consider the element where point O has a z value equal to zero. The applied forces and the stress resultants on the differential element are shown in the following.

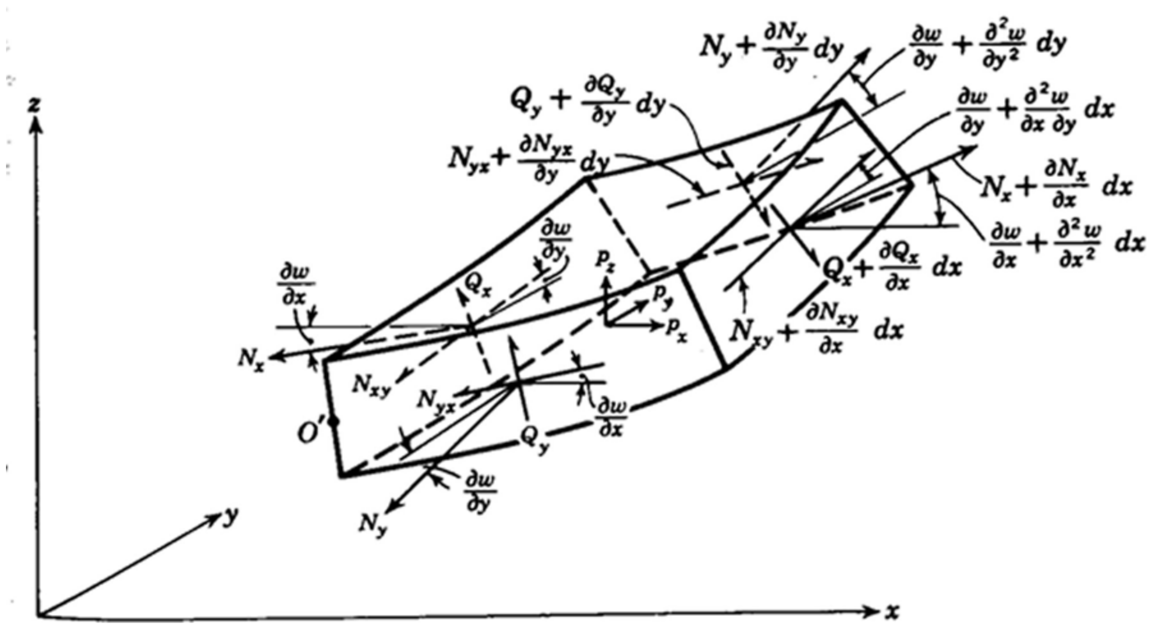


Figure 79 Applied forces and Stress resultants

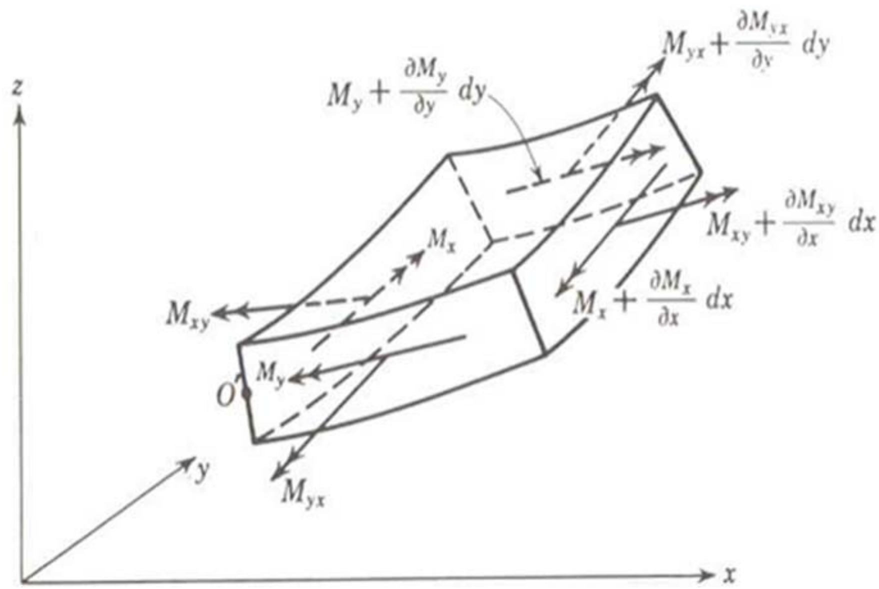


Figure 80 Moments acting on the plate

Components p_x, p_y, p_z remain parallel to the x, y, z axes when the plate deforms. The summation of forces in the x and y direction are given as

$$-N_x dy + \left(N_x + \frac{\partial N_x}{\partial x}dx\right)dy - N_{yx}dx + \left(N_{yx} + \frac{\partial N_{yx}}{\partial y}dy\right)dx + p_x dxdy = 0 \tag{6.9}$$

which reduces to

$$\frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} + p_x = 0 \tag{6.10}$$

and similarly for the y-axis,

$$\frac{\partial N_y}{\partial y} + \frac{\partial N_{yx}}{\partial x} + p_y = 0 \tag{6.11}$$

where N_x , N_y are the forces acting normal along the x and y directions. N_{yx} and N_{xy} are the shear forces, respectively.

These equations assume small angle approximation and equating moments about an axis which is parallel to the z-axis and passes through the center of the element, we obtain $N_x = N_y$. The summation of the moments result in

$$M_x dy - \left(M_x + \frac{\partial M_x}{\partial x}dx\right)dy - M_{yx}dx + \left(M_{yx} + \frac{\partial M_{yx}}{\partial y}dy\right)dx +$$

$$Q_x \frac{dx}{2}dy + \left(Q_x + \frac{\partial Q_x}{\partial x}dx\right)\frac{dx}{2}dy = 0 \tag{6.12}$$

Simplification of this equation results in

$$\frac{\partial M_x}{\partial x} - \frac{\partial M_{yx}}{\partial y} - Q_x = 0 \tag{6.13}$$

and

$$\frac{\partial M_{xy}}{\partial x} - \frac{\partial M_y}{\partial y} - Q_x = 0 \tag{6.14}$$

The summation of forces acting in the z-direction are given as

$$\frac{\partial^2 M_x}{\partial x^2} + 2\frac{\partial^2 M_{xy}}{\partial x \partial y} + \frac{\partial^2 M_y}{\partial y^2} = p_x + N_x \frac{\partial^2 w}{\partial x^2} + 2N_{xy}\frac{\partial^2 w}{\partial x \partial y} + N_y \frac{\partial^2 w}{\partial y^2} - p_x \frac{\partial w}{\partial x} - p_y \frac{\partial w}{\partial y} \tag{6.15}$$

Assuming that the normals to the reference surface remain normal to the surface and unchanged in length as the plate deforms ($\varepsilon_{xz} = \varepsilon_{yz} = \varepsilon_{zz}$ =0) [4], and by Von-Karman assumption that the plate is more flexible in the transverse direction than in the in-plane direction, the strain – displacement compatibility equations are given as

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} - z\frac{\partial^2 w}{\partial x^2} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 \tag{6.16}$$

$$\varepsilon_{yy} = \frac{\partial v}{\partial y} - z\frac{\partial^2 w}{\partial y^2} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 \tag{6.17}$$

$$\varepsilon_{xy} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} - 2z\frac{\partial^2 w}{\partial x \partial y} + \frac{\partial w}{\partial x}\frac{\partial w}{\partial y} \tag{6.18}$$

$$\frac{\partial^2 \varepsilon_{yy}}{\partial x^2} + \frac{\partial^2 \varepsilon_{xx}}{\partial y^2} = \frac{\partial^2 \varepsilon_{xy}}{\partial x \partial y} + \left(\frac{\partial^2 w}{\partial x \partial y}\right)^2 - \frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} \tag{6.19}$$

where ε_{xx} , ε_{yy} are the strains in x and y directions respectively. ε_{xy} is the shearing strain. u, v, w are the displacements along the x, y, and z directions.

Due to the assumed 2-D stress-strain relation and the assumption that the material used for the mat is linearly elastic and isotropic in the xy plane, the stress-strain equations become

$$\varepsilon_{xx} = \frac{1}{E}\left(\sigma_{xx} - \upsilon\sigma_{yy}\right) - \frac{\upsilon_z}{E_z}\sigma_{zz} \tag{6.20}$$

$$\varepsilon_{yy} = \frac{1}{E}\left(\sigma_{yy} - \upsilon\sigma_{xx}\right) - \frac{\upsilon_z}{E_z}\sigma_{zz} \tag{6.21}$$

Some terms like the modulus in the z direction, the Poisson's ratio and the shear modulus existing between the z direction and the xy plane are neglected by the assumption that the normal to the reference surface remains normal and unchanged in length, and the equations reduce to the first three plane-stress relations [4]. As such, we have

$$\varepsilon_{yy} = \varepsilon_{yy} = \varepsilon_{yy} = v_2 = \alpha_2 = 0 \tag{6.22}$$

$$E_z = G_z = \infty \tag{6.23}$$

$$\sigma_{zz} << \sigma_{xx}, \sigma_{yy} \tag{6.24}$$

and the shear deformations are small compared to bending deformations in a thin plate [7]. The Stress values in terms of displacements are given as,

$$\sigma_{xx} = \frac{E}{1-v^2}\left\{\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} - z\left(\frac{\partial^2 w}{\partial x^2} + v\frac{\partial^2 w}{\partial y^2}\right) + \frac{1}{2}\left[\left(\frac{\partial w}{\partial x}\right)^2 + v\left(\frac{\partial w}{\partial y}\right)^2\right]\right\} \tag{6.25}$$

$$\sigma_{yy} = \frac{E}{1-v^2}\left\{\frac{\partial v}{\partial y} + v\frac{\partial u}{\partial x} - z\left(\frac{\partial^2 w}{\partial y^2} + v\frac{\partial^2 w}{\partial x^2}\right) + \frac{1}{2}\left[\left(\frac{\partial w}{\partial y}\right)^2 + v\left(\frac{\partial w}{\partial x}\right)^2\right]\right\} \tag{6.26}$$

$$\sigma_{xy} = \frac{1}{2}\frac{E}{(1+v)}\left\{\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} - 2z\frac{\partial^2 w}{\partial x \partial y} + \frac{\partial w}{\partial x}\frac{\partial w}{\partial y}\right\} \tag{6.27}$$

Plate Equations

The thin plate equations can be derived by analyzing the in-plane stress resultants

$$N_x = K^*\left\{\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} + \frac{1}{2}\left[\left(\frac{\partial w}{\partial x}\right)^2 + v\left(\frac{\partial w}{\partial y}\right)^2\right]\right\} \tag{6.28}$$

$$N_y = K^*\left\{\frac{\partial v}{\partial y} + v\frac{\partial u}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial w}{\partial y}\right)^2 + v\left(\frac{\partial w}{\partial x}\right)^2\right]\right\} \tag{6.29}$$

$$N_{xy} = \frac{1}{2}\frac{K^*(1+v)}{}\left\{\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial w}{\partial x}\frac{\partial w}{\partial y}\right\} \tag{6.30}$$

where $K^* = \dfrac{E_1 t^*}{1-v^2}$ is the extensional stiffness per unit length of the plate.

Poisson's ratio is a measure of the simultaneous change in elongation and in cross-sectional area within the elastic range when tensile forces are applied. The reduction in cross-sectional area is proportional to the increase in length in the elastic range by a dimensionless factor. It is assumed v is constant, as v differs only slightly as a function of position for most structural materials, with respect to thin plate theory [6]. As such the moments are written as

$$M_x = D^* \left\{ \left(\frac{\partial^2 w}{\partial x^2} \right) + v \left(\frac{\partial^2 w}{\partial y^2} \right) \right\} \tag{6.31}$$

$$M_y = D^* \left\{ \left(\frac{\partial^2 w}{\partial y^2} \right) + v \left(\frac{\partial^2 w}{\partial x^2} \right) \right\} \tag{6.32}$$

$$M_{xy} = D^* (1 - v) \left(\frac{\partial^2 w}{\partial x \partial y} \right) \tag{6.33}$$

where the modulus weighted bending rigidity per unit length of the plate is given as

$$D^* = \frac{E}{1 - v^2} \int_t z^2 dz^* \tag{6.34}$$

Since the plate is considered for first analysis as a homogenous plate, $t^* = t$ and K^*, D^* become

$$K^* = \frac{E_1 t}{1 - v^2} \qquad D^* = \frac{E t^3}{12(1 - v^2)} \tag{6.35}$$

The stresses can be expressed in terms of the modulus-weighted values

$$\sigma_{xx} = \frac{E}{E_1} \left(\frac{N_x}{t} - \frac{M_x z}{\bar{I}} \right) \tag{6.36}$$

$$\sigma_{yy} = \frac{E}{E_1} \left(\frac{N_y}{t} - \frac{M_y z}{\bar{I}} \right) \tag{6.37}$$

$$\sigma_{xy} = \frac{E}{E_1} \left(\frac{N_{xy}}{t} - \frac{M_{xy} z}{\bar{I}} \right) \tag{6.38}$$

when the plate is considered to be homogenous. For this condition $\bar{I} = t^3/12$. In case of laminated plates $\bar{I} = \int_t z^2 dz^*$.

The equilibrium equation for the z-direction can be expressed in terms of w, when D* is a constant as

$$\nabla^4 w = \frac{1}{D^*} \left(-\frac{\partial V}{\partial z} + N_x \frac{\partial^2 w}{\partial x^2} + 2N_{xy} \frac{\partial^2 w}{\partial x \partial y} + N_y \frac{\partial^2 w}{\partial y^2} + \frac{\partial V}{\partial x}\frac{\partial w}{\partial x} + \frac{\partial V}{\partial y}\frac{\partial w}{\partial y} \right) \tag{6.39}$$

Equation 6.39 is the stress-function-lateral displacement formulation of plate theory and

$$\nabla^4 w = \frac{\partial^4 w}{\partial x^4} + \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \tag{6.40}$$

Equation 6.40 is the governing equation for plate bending theory, also called the biharmonic equation where the higher order terms are neglected. V(x,y) is a potential function.

Chapter 7. Equivalent Mat Analysis

Introduction of Honeycomb Mats

This chapter presents the analysis of an equivalent composite mat. The plate equations from the last chapter are modified based on laminate theory. PATRAN [15] uses this algorithm to simulate the laminate structure.

A non-homogenous plate has nonuniform properties over the plate, that is, the properties are a function of position of the plate [5]. The Aluminum honeycomb mats have been used for most of the Rapid Runway Repairs as a Foreign Object Damage cover. Aluminum alloys have very high strength and wear resistance. Most of the honeycomb panels are manufactured lightweight but strong, utilizing fiberglass, aluminum and carbon skin materials. The honeycomb structure gives an optimal strength to weight ratio. Normally, the honeycomb mat has a honeycomb panel sandwiched between two aluminum panels at the top and bottom of it. The panels are either glued or pressed at required temperatures to form the mat. Most of the mats have a core cell size of 6 mm and foil thickness of 7 um. Aluminum mats are known for their good fatigue resistance and they are sometimes used as a fireproof material. This chapter presents the equations for a composite model. This analysis is taken from the laminate theory explained by Jones [5] and from the PATRAN manual [15] and is included herein for completeness.

The honeycomb lamina is considered to be an equivalent mat with almost 1/100-1/50 of the original density of its material. This assumption is justified by considering a honeycomb cell and replacing it with a small unit cell with lesser density. If the thickness and material of all thin walls that make the honeycomb cell are added, they are equal to approximately 1/50 of a whole cell. The figure below shows the Honeycomb panel sandwiched between the upper and lower panels.

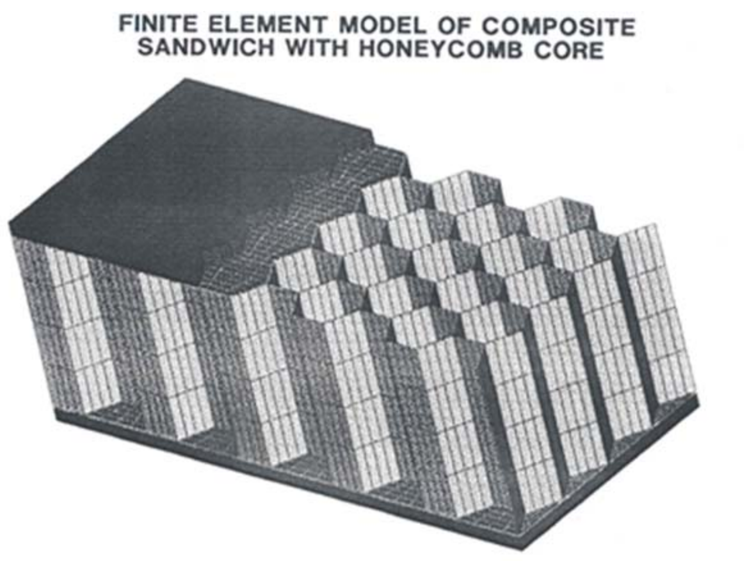


Figure 81 Model of a composite sandwich with honeycomb core

Modeling of Equivalent Mat

The modeling of the equivalent mat is based on the idea that the middle ply, which is the honeycomb panel, can be reduced to an equivalent panel which is made of the same material but of lesser density. So a panel structure analysis is very important to study the behavior of the panel under different load and boundary conditions. According to laminate theory, the inner honeycomb panel will be replaced to an equivalent panel (conventional approach). This chapter presents the equations for a composite model. This is also analyzed for completeness.

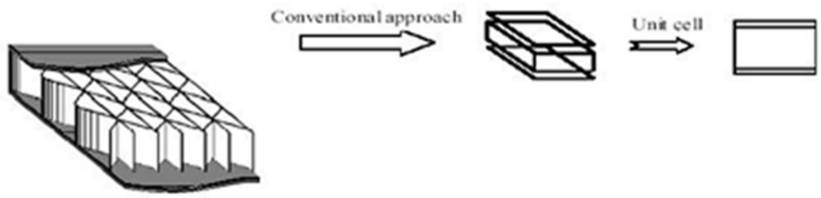


Figure 82 Conventional approach for honeycomb equivalence

Since the honeycomb panel is substituted by an equivalent plate (by laminate theory), the plate is assumed to exhibit the properties of an original plate. This assumption allows the model to be simulated with a constant Poisson's ratio. The middle panel has a density of 55.9 kg/m^3 and shear modulus along xy, xz, yz to be 25 x 10^9 N/m^2.

Basically, the resultant forces and moments acting on the laminate structure are given as,

$$N_X = \int_{-t/2}^{t/2} \sigma_X \, dz \qquad M_X = \int_{-t/2}^{t/2} \sigma_X \, z dz \tag{7.1}$$

where N_x is the force per unit length of the cross section of the laminate and M_x is the moment per unit length. The coordinate axes are shown in Figure 4-3. Considering all forces and moments, we have

$$\begin{Bmatrix} N_X \\ N_Y \\ N_{XY} \end{Bmatrix} = \int_{-t/2}^{t/2} \begin{Bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{Bmatrix} dz = \sum_{K=1}^{N} \int_{z_{K-1}}^{z_K} \begin{Bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{Bmatrix}_k dz \tag{7.2}$$

and

$$\begin{Bmatrix} M_X \\ M_Y \\ M_{XY} \end{Bmatrix} = \int_{-t/2}^{t/2} \begin{Bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{Bmatrix} zdz = \sum_{K=1}^{N} \int_{z_{K-1}}^{z_K} \begin{Bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{Bmatrix}_k zdz \tag{7.3}$$

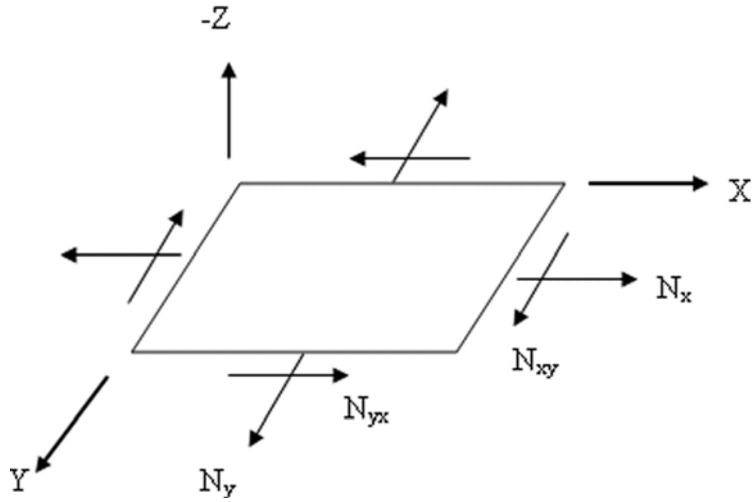


Figure 83 Force components on the plate

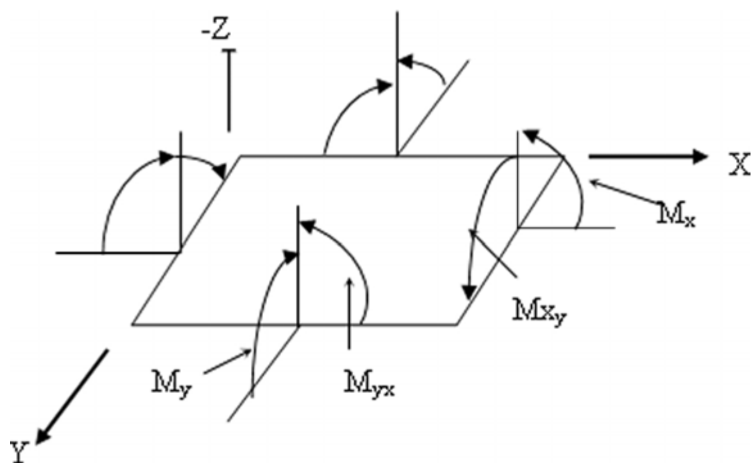


Figure 84 Moments on the plate

where they are integrated for thickness t (-t/2 to t/2). Figure 4-3 and 4-4 show the force and moment components acting on the plate respectively. The forces and moments are dependent on x and y, but are independent of z. The stiffness matrix of the lamina is constant within the lamina, so the equations can be written as

$$\begin{Bmatrix} N_X \\ N_Y \\ N_{XY} \end{Bmatrix} = \sum_{K=1}^{N} \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_K \left\{ \int_{Z_{K-1}}^{Z_K} \begin{Bmatrix} \varepsilon_X^0 \\ \varepsilon_Y^0 \\ \gamma_{XY}^0 \end{Bmatrix} dz + \int_{z_{K-1}}^{z_K} \begin{Bmatrix} \kappa_X \\ \kappa_Y \\ \kappa_{XY} \end{Bmatrix} zdz \right\} \quad (7.4)$$

and

$$\begin{Bmatrix} M_X \\ M_Y \\ M_{XY} \end{Bmatrix} = \sum_{K=1}^{N} \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_K \left\{ \int_{Z_{K-1}}^{Z_K} \begin{Bmatrix} \varepsilon_X^0 \\ \varepsilon_Y^0 \\ \gamma_{XY}^0 \end{Bmatrix} zdz + \int_{z_{K-1}}^{z_K} \begin{Bmatrix} \kappa_X \\ \kappa_Y \\ \kappa_{XY} \end{Bmatrix} z^2 dz \right\} \quad (7.5)$$

where ε_X^0, ε_Y^0, γ_{XY}^0 are the middle surface laminate strains by virtue of Kirchhoff - Love hypothesis [5] and κ_X, κ_Y, κ_{XY} are the middle surface curvatures. The values of the ε_X^0, ε_Y^0, γ_{XY}^0, κ_X, κ_Y, κ_{XY} are not functions of z.

$$\begin{Bmatrix} N_X \\ N_Y \\ N_{XY} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_X^0 \\ \varepsilon_Y^0 \\ \gamma_{XY}^0 \end{Bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{Bmatrix} \kappa_X \\ \kappa_Y \\ \kappa_{XY} \end{Bmatrix} \tag{7.6}$$

and

$$\begin{Bmatrix} M_X \\ M_Y \\ M_{XY} \end{Bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_X^0 \\ \varepsilon_Y^0 \\ \gamma_{XY}^0 \end{Bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \kappa_X \\ \kappa_Y \\ \kappa_{XY} \end{Bmatrix} \tag{7.7}$$

where,

$A_{ij} = \sum_{k=1}^{N} \left(\overline{Q}_{ij}\right)_k \left(z_k - z_{k-1}\right)$ is the Generalized Extensional Stiffness

$B_{ij} = \frac{1}{2} \sum_{k=1}^{N} \left(\overline{Q}_{ij}\right)_k \left(z_k^2 - z_{k-1}^2\right)$ is the Generalized Coupling Stiffness

$D_{ij} = \frac{1}{3} \sum_{k=1}^{N} \left(\overline{Q}_{ij}\right)_k \left(z_k^3 - z_{k-1}^3\right)$ is the Generalized Bending Stiffness.

It is impossible to pull on a laminate that has B_{ij} terms without bending or twisting the laminate at the same instant. Extensional deformation occurs with twisting and/or bending of the laminate when an extension force is applied. Such a laminate cannot be subjected to a moment without taking into account the extension of the middle surface at the same instant.

In pure plate bending problems, the extensional stiffnesses are neglected and bending stiffnesses are taken into account. An assumption of symmetrical laminate is also made so that it coincides with the plate analysis, which is discussed in the following chapter. A unit area of the plate with unit force conditions is considered, to simulate this structure.

For laminates that are symmetric both in geometry and material properties about the middle surface, the general stiffness equations reduce considerably. For any layer, because of the symmetry of $\left(\overline{Q}_{ij}\right)$ and the thickness, t, the coupling stiffness goes to zero [5]. Hence the pure bending stresses are analyzed. The force and moment resultants for a symmetric laminate are

$$\begin{Bmatrix} N_X \\ N_Y \\ N_{XY} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_X^0 \\ \varepsilon_Y^0 \\ \gamma_{XY}^0 \end{Bmatrix} \tag{7.8}$$

and

$$\begin{Bmatrix} M_X \\ M_Y \\ M_{XY} \end{Bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \kappa_X \\ \kappa_Y \\ \kappa_{XY} \end{Bmatrix} \tag{7.9}$$

If the multiple isotropic layers of various thicknesses are arranged symmetrically about the middle surface from a geometric and material standpoint, the resulting laminate does not exhibit coupling in bending and extension [12]. A three isotropic-layered symmetric laminate is shown below.

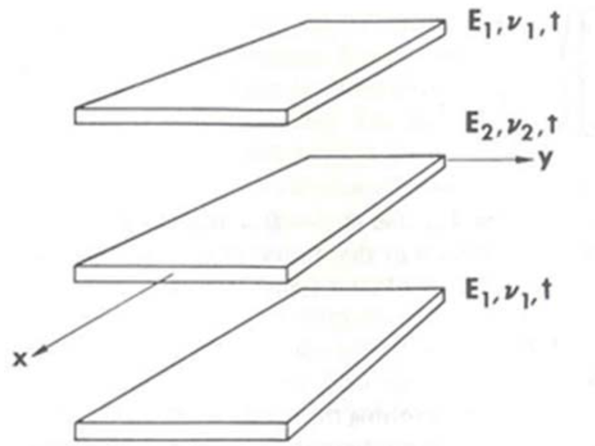


Figure 85 Exploded view of the symmetric laminate structure

The extension and bending stiffness is calculated to be

$$(\overline{Q}_{11})_k = (\overline{Q}_{22})_k = \frac{E_k}{1-\upsilon_k^2}$$

$$(\overline{Q}_{16})_k = (\overline{Q}_{26})_k = 0$$

$$(\overline{Q}_{12})_k = \frac{\upsilon_k E_k}{1-\upsilon_k^2}$$

$$(\overline{Q}_{66})_k = \frac{E_k}{2(1+\upsilon_k)} \tag{7.10}$$

and the force and moment resultants become

$$\begin{Bmatrix} N_X \\ N_Y \\ N_{XY} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_X^0 \\ \varepsilon_Y^0 \\ \gamma_{XY}^0 \end{Bmatrix} \tag{7.11}$$

and

$$\begin{Bmatrix} M_X \\ M_Y \\ M_{XY} \end{Bmatrix} = \begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & D_{66} \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \kappa_Y \\ \kappa_{XY} \end{Bmatrix} \tag{7..12}$$

for isotropic layers, $A_{11}=A_{22}$ and $D_{11}=D_{22}$

Laminates are be made of orthotropic layers that have principal material directions aligned with the laminate axis. If the thickness, locations, and material properties of the laminae are symmetric about the middle surface of the laminate, there is no coupling between bending and extension. The bending and extension stiffness are given as

$$\begin{aligned} \left(\overline{Q}_{11}\right)_k &= \frac{E_1^k}{1-\upsilon_{12}^k\upsilon_{21}^k} & \left(\overline{Q}_{16}\right)_k &= 0 \\ \left(\overline{Q}_{12}\right)_k &= \frac{\upsilon_{21}^k E_1^k}{1-\upsilon_{12}^k\upsilon_{21}^k} & \left(\overline{Q}_{26}\right)_k &= 0 \\ \left(\overline{Q}_{22}\right)_k &= \frac{E_2^k}{1-\upsilon_{12}^k\upsilon_{21}^k} & \left(\overline{Q}_{66}\right)_k &= 0 \end{aligned} \tag{7.13}$$

The stiffnesses A_{16}, A_{26}, D_{16} and D_{26} are zero as $\left(\overline{Q}_{16}\right)_K$, $\left(\overline{Q}_{26}\right)_K$ are zero. If the laminae are of the same thickness and material properties but vary with laminate axes at 0^o and 90^o, the material is referred to as cross-ply laminate. The coupling between bending and extension vanishes when the laminate has an odd number of layers, to meet the symmetry conditions [5]. The honeycomb mat structure can be considered an equivalent layer with a cross ply angle. The extensional stiffness A_{ij}, are the sum of the product of laminae thickness and the individual laminae $\left(\overline{Q}_{ij}\right)$ [5]. If some $\left(\overline{Q}_{ij}\right)$ have negative values and some have positive values so that the products with respective thicknesses sum to zero, then the individual A_{ij} equals to zero. The $\left(\overline{Q}_{11}\right)$, $\left(\overline{Q}_{12}\right)$, $\left(\overline{Q}_{22}\right)$ and $\left(\overline{Q}_{66}\right)$ are positive definite and A_{11}, A_{12}, A_{22} and A_{66} are positive definite too since the thicknesses are always positive.

If the lamina orientations are considered to be at 0^o and 90^o then $\left(\overline{Q}_{16}\right)$ and $\left(\overline{Q}_{26}\right)$ are zero. The values of A_{16} and A_{26} are zero for orthotropic laminae oriented at 0^o or 90^o. If the cross-ply laminate is symmetric about the middle surface, then B_{ij} vanishes. In the case of bending stiffnesses, the D_{ij} are the product of individual laminae $\left(\overline{Q}_{ij}\right)$ and $\left(z_k^3 - z_{k-1}^3\right)$. $\left(\overline{Q}_{16}\right)$ and $\left(\overline{Q}_{26}\right)$ are zero if the lamina principal material property orientations are 0^o and 90^o and so $\left(D_{16}\right)$ and $\left(D_{26}\right)$ are zero. Since the geometric term and $\left(\overline{Q}_{11}\right)$, $\left(\overline{Q}_{12}\right)$, $\left(\overline{Q}_{22}\right)$ and $\left(\overline{Q}_{66}\right)$ are positive definite, $\left(D_{11}\right)$, $\left(D_{12}\right)$, $\left(D_{22}\right)$ and $\left(D_{66}\right)$ are positive definite.

A laminate of multiple orthotropic layers, which is symmetrical about the mid surface, has no coupling between bending and extension and implies that B_{ij} are zero. So the force and moment resultants are similar to the force and moment resultants of a symmetric laminate. The A_{ij} and D_{ij} are required because of coupling between normal forces and shearing strain, shearing force and normal strains, normal moments and twist, and twisting moment and normal curvatures, which can be viewed by the A_{16}, A_{26}, D_{16}, D_{26} stiffnesses. The regular symmetric angle-ply laminates have orthotropic laminates of equal thicknesses. The adjacent laminae have opposite signs of the angle of orientation of the principal material properties with respect to the laminate axes. Normally they take the form of $+\alpha/-\alpha/+\alpha$. As discussed before for symmetry an odd number of layers is chosen and in the case of honeycomb, it is considered to be a three-layered regular symmetric angle-ply laminate. A_{16}, A_{26}, D_{16}, D_{26} take larger values when N=3, which is the number of plies of the equivalent mat structure. These values decrease in proportion to 1/N as N increases.

$$\left(\overline{Q}_{16}\right)_{\alpha} = -\left(\overline{Q}_{16}\right)_{-\alpha} \tag{7.14}$$

holds for both A_{16} and D_{16} as the geometric term multiplying $\left(\overline{Q}_{16}\right)_k$ is the same for two layers symmetrical about the middle surface, which shows their alternating signs and for a multiple layered laminate A_{16}, A_{26}, D_{16} and D_{26} values can be quite small when compared to other values. Considering a symmetric angle-ply laminate, which offers more shear stiffness than a cross-ply laminate, requires more significant analysis.

Formulation of the Laminate Model

For the laminate model, the PATRAN-ABAQUS Software [15] uses Classical Lamination Theory to calculate the membrane, bending and membrane-bending coupling stiffness for a laminated shell [15]. Classical Lamination theory assumes that each layer is in state of plane stress, which implies that the transverse stresses are all zero, that is

$$\sigma_{31} = \sigma_{23} = \sigma_{33} = 0. \tag{7.15}$$

This theory also assumes that the surface normals remain normal when the laminate deforms, so that

$$\varepsilon_i = \varepsilon_i^0 + z\kappa_i \quad \text{for i = 11, 22, 33} \tag{7.16}$$

where ε_i is the strain, ε_i^0 is the mid surface strain, z is the distance from the neutral surface and κ_i is the curvature.

As derived before,

$$Q_{11} = \frac{E_{11}}{\left(1-\upsilon_{12}\upsilon_{21}\right)}$$

$$Q_{22} = \frac{E_{22}}{\left(1-\upsilon_{12}\upsilon_{21}\right)}$$

$$Q_{12} = \frac{\upsilon_{21}E_{11}}{\left(1-\upsilon_{12}\upsilon_{21}\right)} = \frac{\upsilon_{12}E_{22}}{\left(1-\upsilon_{12}\upsilon_{21}\right)}$$

$$Q_{33} = G_{12} \tag{7.17}$$

So when the theory assumption, a state of plane stress, is applied for an orthotropic ply, the constitutive equation can be written as

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} \tag{7.18}$$

The Constitutive matrix $\left[\bar{Q}\right]$ for a layer in the laminate frame can be written as

$$\left[\overline{Q}\right] = \left[T\right]^T \left[Q\right]\left[T\right] \tag{7.19}$$

where

$$\left[T\right] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\cos\theta\sin\theta \\ \sin^2\theta & \cos^2\theta & -2\cos\theta\sin\theta \\ -\cos\theta\sin\theta & \cos\theta\sin\theta & -\sin^2\theta \end{bmatrix} \tag{7.20}$$

[T] is the matrix transforming the laminate frame strain into the ply frame and θ is the respective transformation angle from the laminate frame to the ply frame.

The expression for the first kinematic assumption with the constitutive equation for the kth ply combines to form

$$\left\{\sigma_k\right\} = \left[\overline{Q_K}\right]\left\{\varepsilon_K\right\}$$

$$\left\{\sigma_1\right\} = \left[\overline{Q_1}\right]\left\{\varepsilon_1\right\}$$

$$\left\{\sigma_2\right\} = \left[\overline{Q_2}\right]\left\{\varepsilon_2\right\}$$

$$\left\{\sigma_3\right\} = \left[\overline{Q_3}\right]\left\{\varepsilon_3\right\} \tag{7.21}$$

which would yield, with respect to the assumption of the Classical Lamination theory,

$$\{\sigma_k\} = [\overline{Q}_K]\{\varepsilon^0\} + z[\overline{Q}_K]\{\kappa\} \tag{7.22}$$

Also it is already known that

$$\{N\} = \int \sigma dz \quad \text{and} \quad \{M\} = \int \sigma z dz \tag{7.23}$$

where, N is the force per unit length and M is the moment per unit length. So, substituting equation 7.22 into equation 7.23 we obtain,

$$\{N\} = \int [\overline{Q}_k]\{\varepsilon^0\}dz + \int [\overline{Q}_k]z\{\kappa\}dz \tag{7.24}$$

and

$$\{M\} = \int [\overline{Q}_k]z\{\varepsilon^0\}dz + \int [\overline{Q}_k]z^2\{\kappa\}dz \tag{7.25}$$

and the mid surface strains ε^0 and the curvature κ are independent of z and $\overline{Q}_k$ is constant within each ply. So the equations obtain the form

$$\{N\} = \{\varepsilon^0\}\sum_{K=1}^{n}[\overline{Q}_K]\{h_k - h_{k-1}\}dz + \frac{1}{2}\{\kappa\}\sum_{k=1}^{n}[\overline{Q}_k](h_k - h_{k-1}) \tag{7.26}$$

and

$$\{M\} = \frac{1}{2}\{\varepsilon^0\}\sum_{K=1}^{n}[\overline{Q}_K]\{h^2{}_k - h^2{}_{k-1}\}dz + \frac{1}{3}\{\kappa\}\sum_{k=1}^{n}[\overline{Q}_k](h^3{}_k - h^3{}_{k-1}) \tag{7.27}$$

where h_k is the coordinate of the top of the k^{th} ply.

From these equations the stiffness matrices for bending behavior and membrane-bending behavior can be extracted and found to be

$$[D] = \frac{1}{3}\sum_{k=1}^{n}[\overline{Q}_k](h^3{}_k - h^3{}_{k-1}) \tag{7.28}$$

and

$$[B] = \frac{1}{2}\sum_{k=1}^{n}[\overline{Q}_k](h^2{}_k - h^2{}_{k-1}) \tag{7.29}$$

Summary

This chapter studies the analytical equations involved in an equivalent mat system. The honeycomb mats are generally used for road repair. Hence this analysis on the honeycomb mat, considering its honeycomb panel to be an equivalent panel would help in reducing complicated analysis of a honeycomb panel. The derivations presented in this chapter are to obtain an idea of what equations would be involved when running the simulation. Further chapters describe how this model was simulated and analyses the results obtained from those simulations.

Chapter 8. Modeling of the Structure

Basic Structure of the Aluminum Mat

The goal of this part of the research has been to determine the optimal locations to simply support a plate, which can be loaded at any location by a point load. That is, the support locations will be identified that minimize the maximum stress for point loading at any point on the plate. While highly idealized, this result will assist in our understanding of the best possible places to support the mats when considering their use for rapid road repair.

The concepts of the RRR process to repair the pavement damage can still be personalized to make the process less tedious and efficient. To achieve the intended, it is anticipated that the plate designed should act as an equivalent FOD cover with a filled crater. An analysis on the plate structure would give a better understanding of the repair procedure. Moreover, an analysis on the existing mats would give a better idea whether or not to use the same structure or design a mat for this repair. In order to perform a reliable repair the mat should take up maximum loads that can be expected, like the trucks that might use the pavement. A design analysis has been done on the mats by optimizing the support conditions. Once analyzed, the model will act as the base case for any derived mat design for any crater damage.

The analysis and simulation of the plate structure has been done using PATRAN-ABAQUS, powerful Finite Element Analysis software [15]. Existing data about the mat has been used to define our model. PATRAN gives us a visual idea of the geometry and shape of the model. It later uses ABAQUS for analysis and gives precise output information with its Graphical User Interface (GUI) capability.

Modeling Assumptions

Several assumptions are employed to develop the model including:

Dimension-independent geometry

Mesh seed

Quasi-static Point Load with Unit Force

Simply supported Boundary Condition

Linear, elastic material property

2D Shell property

These assumptions are discussed in detail to follow.

Assumption on Dimensionless Geometry

The Dimension-independent geometry is an important assumption for the model to be accepted globally. During the modeling of the geometry, the mat is considered as a 1 x 1 x 0.01 dimensionless mat. The dimensions were later varied for the optimization process. The dimensionless condition allows any metric system to be used and gives an unbiased simulation result.

Selection of Mesh Seed

Following a standard finite element mesh convergence method, a 32 x 32 meshing is used. The elements employed are quadrilateral elements. To obtain a precise solution, the mesh seed is initially varied on a particular state variable, for example, displacement. The Convergence plot obtained from the displacement results are plotted against the number of meshes, suggests the optimum mesh seed that could be used on the plate for further analysis. As seen in Figure 5-1, the displacement values converge asymptotically with a finer mesh of 32x32 and above. A mesh of 32x32 would be an optimal mesh, as the convergence to the original value occurs from then on. A high order mesh would consume more memory for the analysis producing almost similar results.

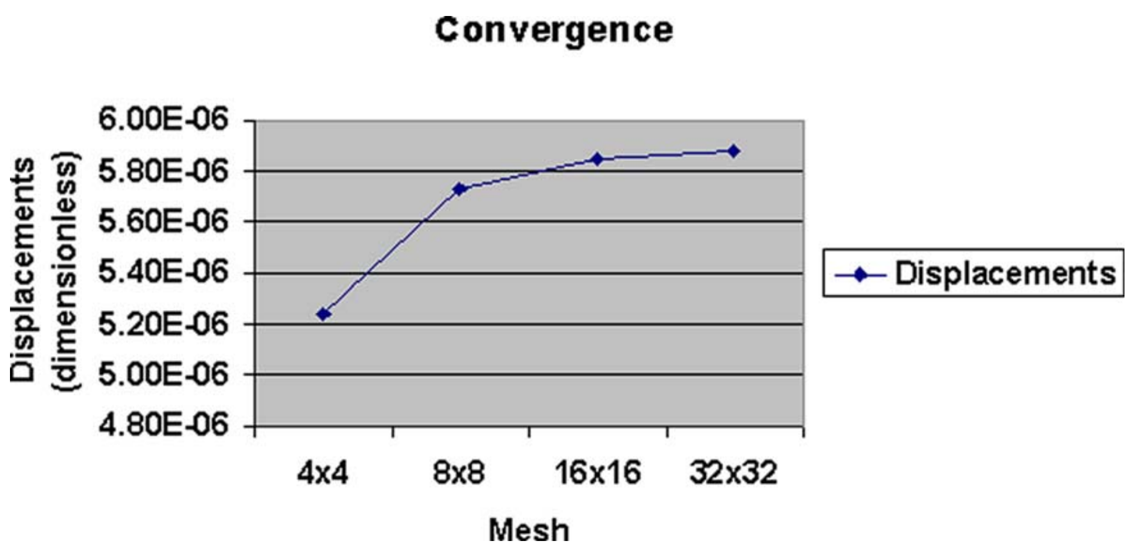


Figure 86 Convergence Plot - Mesh seed versus Displacement

Assumption on Load and Boundary Conditions

The loads on these models would be any traffic, such as a truckload. The forces are considered to act purely normal to the model. The Uniformly Distributed Load (UDL) condition on a certain tire contact section on the mat is neglected and the load is assumed to be a point load. Since the mat has symmetric geometry, the load application can be drastically reduced to one-quarter section of the mat. The unit force condition used in the simulation helps in the non-dimensional analysis. Moreover, the dynamic load condition is constrained to a quasi-static load condition neglecting the time factor. The quasi-static condition reduces the complexity of the problem.

Boundary supports are considered to have a simply supported condition, one end fixed and other ends free. The supports are moved along a diagonal thus maintaining symmetry. The mat would act based on this boundary condition where there is no displacement along the z-axis. Constraining one support for all displacements does not allow the mat to slide.

Assumption on Material and Element Properties

Aluminum [Density = 2796 kg/m^3, Elastic Modulus = 7.2 GPa, Poisson's ratio = 0.31] is considered for the analysis. The plate structure is considered as a shell material with thickness 0.01 (no dimension) initially, and then for optimization checks the thickness and the other dimensions are varied. The thin shell theory can be applied to the model, as the thickness is almost negligible when compared to its other dimensions. The linear and elastic material property is used for analysis as the aluminum mat stays in its elastic area and the linear curve in the stress-strain plot is used.

Modeling Procedure of Plate Structure

Geometry

In order to simulate the mat structure, a model has been created in PATRAN [15]. This GUI application gives the user the capability to view and draw the geometry of the model and later provide the options to simulate with different inputs and conditions. The mat used for RRR is basically a rectangular shaped mat, depending on the crater size. While modeling this structure, the plate is considered as a single part and not a component, which has sub-parts or assemblies. This symmetric geometry allows the user to simulate for all loads and boundary conditions by just applying the loads on a quarter portion of the mat. The assumptions above are valid when the mat structure model is to be considered for a plate extension-bending problem.

The model is created as a unit dimensional symmetric plate. Basically, this would allow increasing any side of the mat proportionally to obtain the original simulation result. The geometry of the mat is made simple and flexible for dimension required in future, as the crater width is not constant and this would affect the length and width of the mat, its orientation, etc. The model has a zero inclination with the X-Y plane. A variation in the angles would produce different results. Generally, the surface to be repaired is considered to have zero inclination, as there would be no upheaval in the case of earthquake damage. The repair site can be leveled, with respect to the undamaged pavement, to deploy the mat.

FEM Nodal Application

Node and element definition plays an important role in the analysis. Once the model geometry is created, the finite element meshing, node optimization, etc are done on the existing model. The desired response parameters for this simulation are the Von-Mises stress values. The surface of the model is meshed with quadrilateral elements and meshes are applied to the edges of the surfaces with uniform distribution. The simulation started with a 4x4 mesh on the plate structure. It would be an optimum idea to first check the system for convergence and later on use that mesh for further analysis. A mesh seed of 4 was selected and optimized. While meshing the plate structure it is better to check for bad elements in the system. Bad element problem occurs in a model two elements, which are supposed to share a boundary or an edge does not match with the number of nodes or the position of nodes. Moreover for example, using a quadratic analysis on one element and a linear analysis on the other would produce bad elements, which could affect the system results as a whole. Equivalence of 0.05 tolerances is provided. A quad4 element topology was chosen for the plate structure. As the model is isomeshed, coincident nodes will exist at boundaries of adjacent curves. Equivalencing reduces the duplicated nodes in the model. The mesh is increased and convergence is found at 32 x 32 mesh. Cuthill-Mckee and Gibbs-Pool-Stockmeyer algorithms for a 32 x 32 mesh on the model are used for the optimization [14].

Loads and Boundary Conditions

Functional assignments such as load conditions, boundary conditions, element properties, material properties are necessary for the model completion. The load and boundary conditions are our area of interest as other properties are predefined. These conditions, basically, interact with the geometry and FEM model. These are variables for our simulation. A quasi-static load condition is assumed, as discussed before. The combinations of different positions of the load and different probabilities of boundary positions are grouped as different sets and each set is used to simulate and obtain a particular result. By simulating all the sets, each combination can be analyzed and conclusions can be made.

A unit load is employed. The FEM results can be scaled to account for any magnitude load. The force is applied normal at points to the mat structure as it is assumed that the tire of the vehicle would be a tangent to the surface of the model and no transverse loads are considered. Loads are applied on predefined points, the nodal locations of the FEM model.

The supports are initially placed at the four corners of the model and are considered simple supports. As discussed before, one end is fully constrained for all translational degrees of freedom, while the rest of the supports are constrained for the translation through z-direction, the axis normal to the surface of the model.

Material and Element Properties

The simulation assumes the general properties of an aluminum mat used for the RRR repair. The material property can also be varied during the simulation process. The thickness of the mat can be varied independent to changing the material property. The material property of aluminum, its density and elastic modulus is defined for analysis. As discussed before, the shell element has been used for the simulation. Shell thickness of 1/100th of the length of the model is initially used and then varied till 1/50th of the same length. The length is also doubled and checked for optimization conditions.

A composite structure is also modeled to simulate the equivalent honeycomb mat structure. The composite model has shear modulus between the laminar plates. The density of the middle layer is proportionally reduced to the density of the honeycomb sandwich panel. The density of the sandwiched panel is reduced to 80 kg/m^3, which was calculated to be equivalent for the honeycomb panel's density. The thickness of the mat is split between the three panels as 0.001 for the cover panels and 0.008 for the sandwiched panel. The equivalent modulus values were calculated and applied. Aluminum Poisson's ratio of 0.31 is used as all the panels are aluminum panels and are equivalent (laminate theory and thin plate theory assumptions) to the single aluminum panel. This would be proved during result analysis. For creating a composite material structure, the composite type is selected with definition of each laminate with its orientation, individual ply thickness and stacked in the required pattern. Our condition assumes no offset from the bottom of the stack relative to the neutral surface, the negative half of the laminate thickness. Classical lamination theory is used to compute shell force-deformation properties. Other properties such as the elasticity matrix are calculated using the volume-weighted averaging.

Load Cases

In order to obtain simulation results for different combinations of load and boundary conditions, the sets are stored in this option and the data is used as input for ABAQUS analysis. The boundary conditions are such that the supports move inwards at constant steps and relative simulation is done with the constant seven positions of the force acting normal to the surface. The input file is generated which is discussed in further topics.

ABAQUS Code and Error Diagnosis

Outline of the ABAQUS Program

The finite element analysis in ABAQUS is defined with an input file with extension *.inp. The input file contains keyword lines and data lines. The input file begins with *HEADING option. It has a pre-defined syntax. The data lines can be further subdivided into model data and history data. The model data defines the nodes, elements, and mat material properties and the initial conditions of our model. Model data such as geometry and material type must be included in the input file. Initial conditions, which define our initial stresses, boundary conditions to impose displacements or rotations, kinematical constraints, tire contact interactions are some of the other data used in our code to define our problem on the model. Model data usually is presented before the *STEP keyword. History data starts after a keyword *STEP. This explains the loading, boundary conditions and response type (which is a basic requirement to define history data). The analysis is performed linearly and statically loaded for the mat analysis. It has the flexibility of initially considering the system load to be static and later the loads can be analyzed for arbitrary positions or simply referred as quasi-static loads.

Simulation and Analysis

In order to simulate, the strategy used is to move the load quasi-statically along the plate, positioning it on different nodes. ABAQUS allows the user to load only on the nodes rather than on any random position between nodes. This is normal and can be achieved by having higher order mesh which would basically comply itself to the convergence and also allow the user to move the load for small increments on the xy plane. This analysis was basically done to get a insight of the stress (Von-mises) that the plate would develop. This would give an idea of where to place the supports to minimize the stress acting on the plate or whether a small tuning of the [E] matrix would produce better stiffness matrix that could counteract the stresses. A trial and error method and experience would help in providing an optimized solution for the problem.

Material selection was done based on the provided information of the Am-2 Aluminum mat. The properties of the plate were proposed to be a two-dimensional thin shell system with homogenous material property. A thickness of 1/100th of the sides of the plate was used as per the information provided about the mats and this would also comply with the thin plate theory. The analysis starts with the plate having a simply supported condition at three corners and a pinned condition at one corner, which allows the plate have unconstrained 5 DOF (u, v, q_x, q_y, q_z) at the three corners and unconstrained 3 DOF (q_x, q_y, q_z) at the pinned corner where u, v are the displacements on the x and y axes respectively and q_x, q_y, q_z are the angular displacements with respect to x, y, z axes. A simple strategy has been used to get the information about various load positions. Since the mat is symmetrical, a diagonal part of the mat can be concentrated upon and the load conditions can be applied on specific nodes available. Logically, the loads can be actually applied on the mid node on the plate, the mid node that lies on the edge of the plate and an averaged node the lies on the diagonal of the square geometry. Further more averaged positions were also chosen to obtain more details of the results.

Result Analysis and Optimization

In the previous chapter, the model was designed for analysis. With a 32 x 32 mesh as the base mesh seed further analysis is accomplished. The goal is to analyze the stress encountered by the mat under load. Maximum Von Mises stress is the objective function or design stress that is to be considered.

Theoretically, Von Mises stress is defined as

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}} \tag{8.1}$$

where $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses.

The step-by-step moved support conditions and the quasi-static load that is applied is shown in Figure 5-2 in detail. The supports shown in the figure are moved inwards and will be analyzed for each node combination. Since the boundary condition is a simple support, it can be seen that one of the four supports is constrained for three translational movements and the rest are constrained for movement along for the z-direction only. This enforces the simply support condition on the mat. The point loads shown as down arrows, represent load acting normal and in negative z-direction on the model.

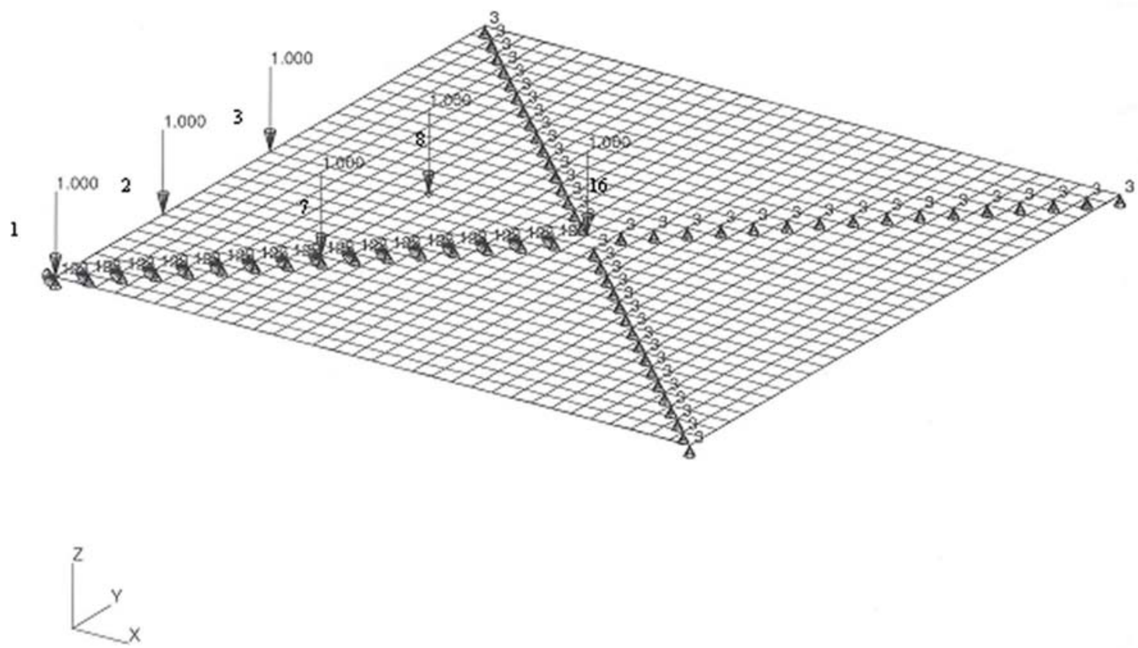


Figure 87 Load and support positions on the model

Typically, it is going to be normal load that the mat experiences. The load acting on the plate is considered to be static thereby using a simplified approach idealizing the problem into tractable problem. Quasi-static load condition is where the load is moved at the certain intervals so that no dynamic effects are experienced. A set of combinations of point loads would actually represent the original load condition.

Moreover the load on the structure cannot be predetermined as the vehicle can take any path on the mat. The vehicles are assumed to pass through the mat structure at lower speeds on the mat where a quasi-static analysis would be appropriate. As it can be seen that the structure is symmetric, point loads are applied on one quarter of the structure.

A unit load on all predefined points is applied. The predefined points are considered due to the symmetrical condition. This gives the flexibility of applying any type of value for the loads and to obtain a respective maximum stress condition and the displacement of the structure. The initial design of the unit dimensional plate will be used for the optimization analysis. The unit load is moved along preset positions. The maximum stress and maximum displacement values are noted for the sixteen boundary conditions for a plate with 32 x 32 mesh. Higher the mesh seed, the accuracy of the positioning of the supports can be refined.

Point loads were placed at node 1, node 2, node 3, node 7, node 8 and node 16. The numbering system was made based on a 4 x 4 meshed mat to start with and was easier for numbering the locations. Basically, these nodes exist even if the mat is meshed with higher mesh seed.

Simulations

Simulation by Moving the Four Corner Supports Towards the Center of the Mat

A logical method to obtain the optimum support positions is to assume the mat has four corner supports. Since the plate structure is symmetrical, the four corners are simply supported with one support constrained for all translations while the rest of the supports are constrained for the z-translation only. Each condition has been shown in Figure 5-3. The non-linear curves plotted shows the maximum stress incurred by the model under the predefined load and boundary conditions. Except for loads at node 1, all the other conditions have certain maximum stress as the load at node 1 acts directly on the support and has no effect on the model. The load at node 7 also acts on the 9th boundary position resulting in zero stress. The ABAQUS input code has been presented in Appendix B for this model.

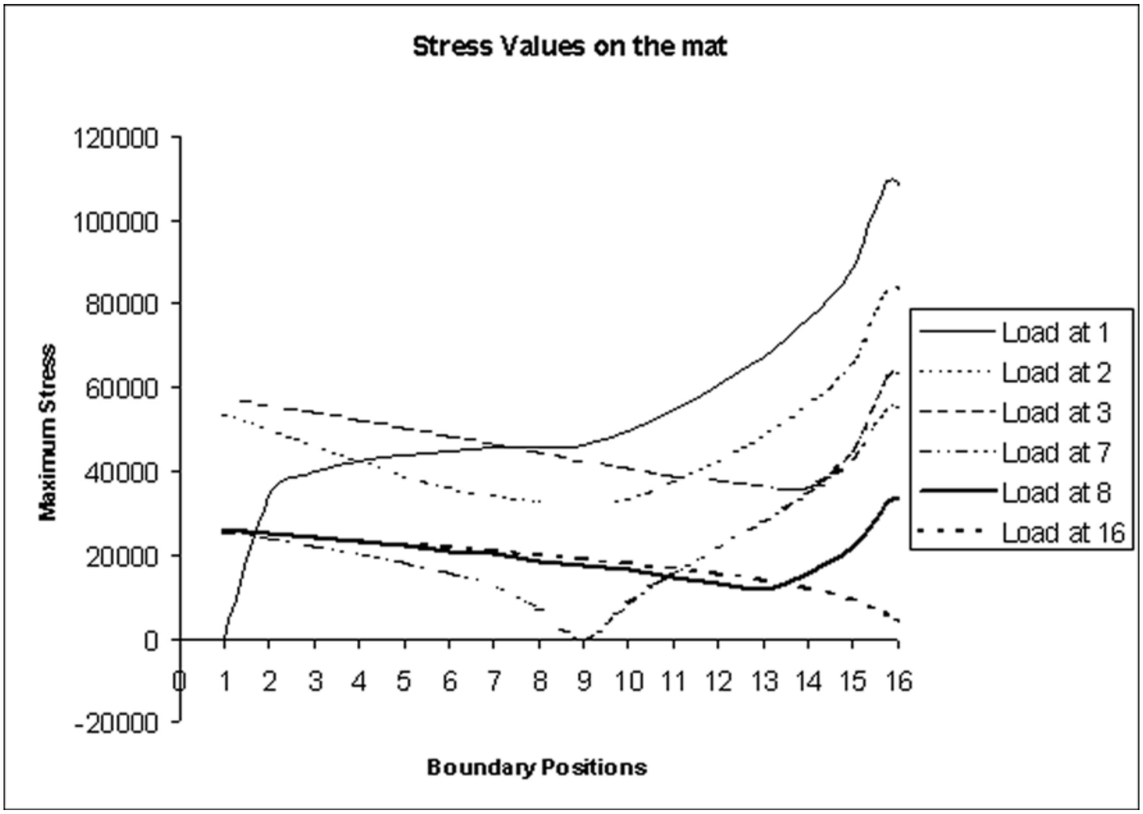


Figure 88 Maximum stress plots (Normal Condition)

Simulation with an Additional Center Support

By adding an additional center support the procedure was repeated to check whether the center support contributed for a reduction of stress values. The values obtained can be found in the Appendix A. A plot of the output is shown in Figure 5-4. From this plot, it can be seen that the values do not have any significant decrease in stress values proving that the additional support does not have a significant impact on the structure. There was a reduction in displacement values when compared with no center support condition. The responses are plotted in the following.

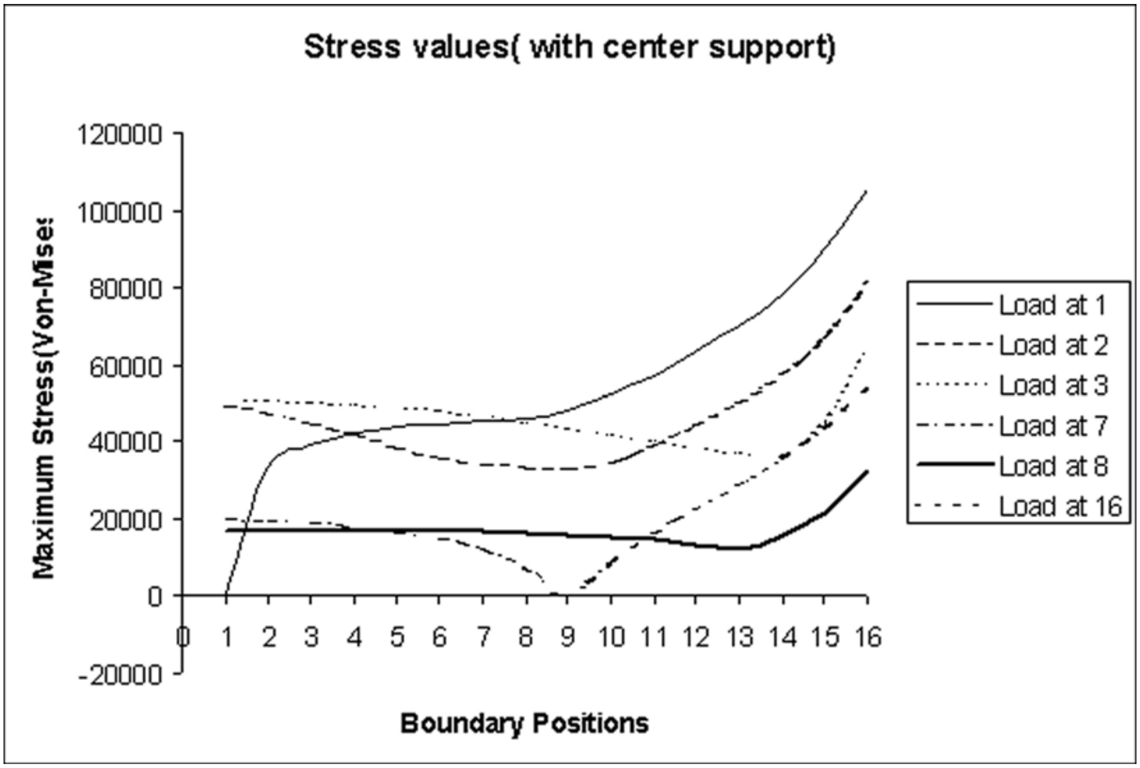


Figure 89 Maximum stress plots (with center support)

Simulation of Honeycomb Structure

In order to analyze the equivalent laminate structure, which was discussed before, the same conditions and constraints are applied on the model. The Maximum stress values are drawn versus the support positions and can be found in the Appendix A. In this case, the plot drawn has similar values to that of the initial mat single lamina structure, which is logical. This also proves the assumptions that were made for analyzing a honeycomb equivalent mat is true. The following shows the response of the honeycomb model.

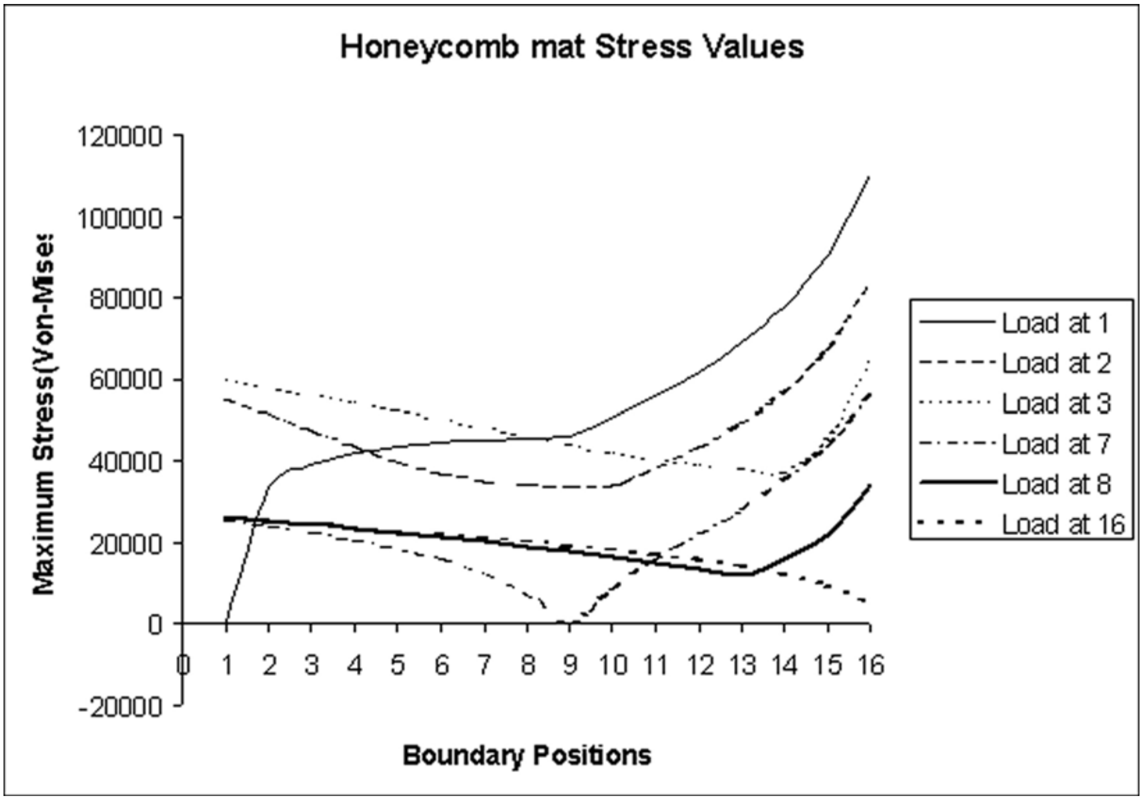


Figure 90 Maximum stress plots (Honeycomb Sandwich model)

Simulation with Increase in Thickness of Mat

The thickness of the mat is a significant factor during the normalization process. During this run, the thickness was increased by a factor of 2, the stress values decrease by a factor of 4. The response remains the same. Figure 5-6 shows the response of the mat with increase in thickness.

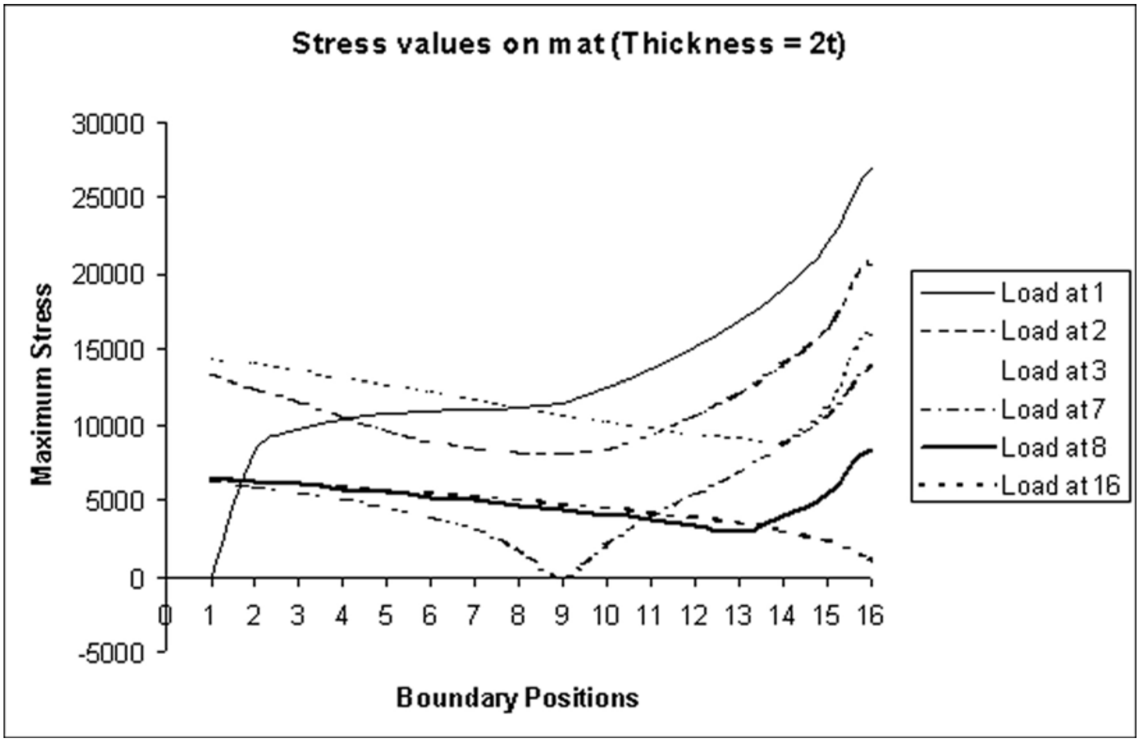


Figure 91 Maximum stress plots (Increase in thickness)

Simulation with the proportionate increase in parametric values of the mat was performed for normalization check.

By varying size, the parameters being F = 1, a = 2, t = 0.01

By varying force factor, the parameters being F = 2, a = 1, t = 0.01

Appendix A shows the displacements and stresses on the mat when the supports are moved in every step, during parameter condition (F = 1, a = 1, t = 0.01). Similar mode shapes were obtained for all combinations of these parameters.

Normalization

Normalization is a process, which involves standardizing a set of related plots, which vary with respect to a factor. When reduced, they converge to one set of X and Y values. To avoid redundancy, normalization process is done.

Normalization involves

Normalization of the maximum Von Mises Stress values

Normalization of the Boundary Supports

Normalizing the maximum Von-Mises stresses would produce a standard set of stress values.

The thickness of the mat affects the process of normalization. A factor $\left(\sigma_{\max} t^2\right)/F$, where $\sigma_{\max}$ is the maximum stress and t is the thickness of the mat.

$$\sigma_{normalized} = \left(\sigma_{\max} t^2\right) / F \tag{8.2}$$

The factor reduces the normalized values to a dimensionless state, which is proved by dimensional analysis.

The dimension of stress is written as $ML^{-1}T^{-2}$, dimension of thickness L^2 and dimension of force MLT^{-2}, where M represents mass values, L represents length and T represents time.

Substituting these dimensions in the normalization equation 8.2

$$\frac{ML^{-1}T^{-2} * L^2}{MLT^{-2}} = \frac{MLT^{-2}}{MLT^{-2}} = 1 \tag{8.3}$$

which proves to be dimensionless. Several test runs were done to confirm that area of the model does not have any impact during the stress normalization process, which the thickness of the mat takes care in standardizing.

Normalization of the boundary conditions should also be done to achieve normalized plots. Since the mesh refining is a 32-seeded mesh and the loads were applied on one quarter mapped area, the diagonal of that square would have 16 positions or node on it where the support is being moved every step. A factor of $\frac{x}{16} * \frac{1}{\sqrt{2}}$, where x is a variable ranging from 1 to 16, each step.

Normalization of both the X-axis values and Y-axis values provide a normalized or standardized plot, which can now be analyzed for optimum support conditions for the model.

The Final Normalized plot is shown in Figure 5-7

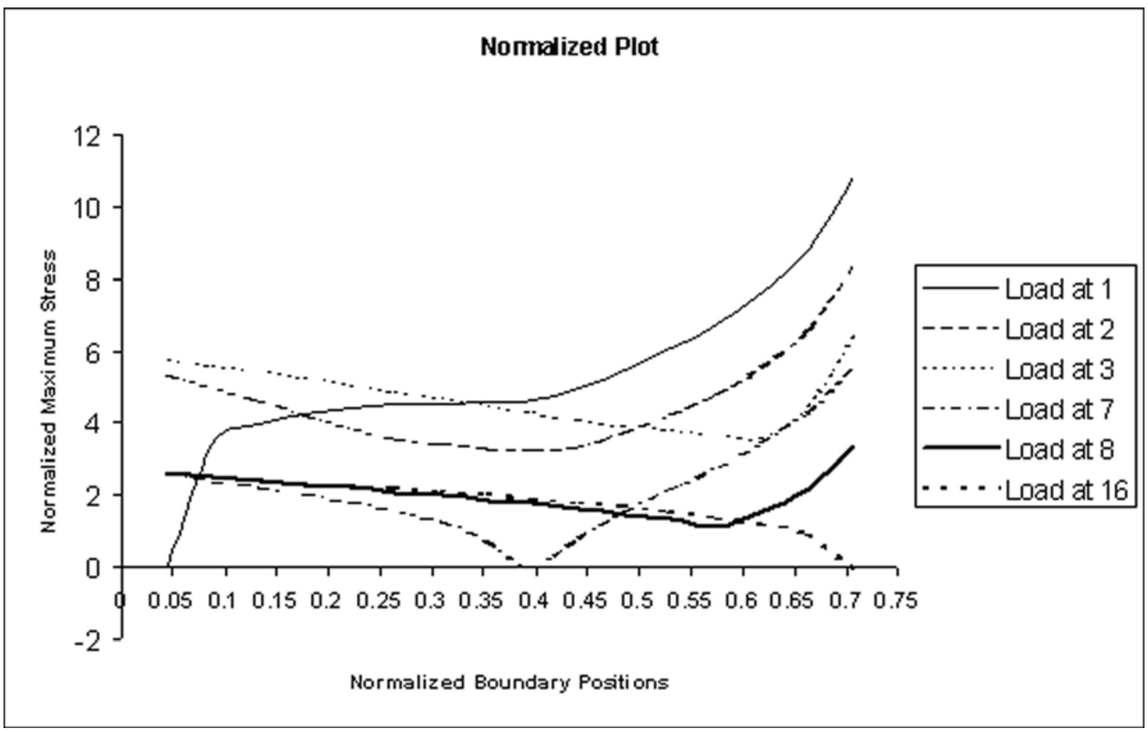


Figure 92 Normalized maximum stress plots

Optimization of Boundary Supports

Optimization of the boundary supports has been one of the goals of this research. Once the simulated results are obtained and plotted, the optimum positions are obtained by analyzing the maximum stresses in the plate, where they are minimized for all possible point load locations. The intersection of curve (Load at 1) and the curve (Load at 3) can be found to be the optimum support location for the mat to withstand load at any point on the mat. The optimum supports are found to lie between the 7th and 8th position, the position where the supports are moved from outside towards the center position, or a normalized 0.3 to 0.35. The optimization technique is a simple but important and efficient procedure, which would allow the user to know the support locations on the mat.

Summary

This chapter discussed the modeling techniques. An unit point load acting on predefined positions on the plate was modeled and the stresses and displacement vector results were recorded with the supports being moved step by step along the diagonal, outwards to inwards. Normally, it is preferred that the load acts on the nodal points on the plate structure. As described, a high order meshing improves the chances of loading at almost all points on the plate. The model is later simulated for various combinations of forces, boundary conditions and thickness. The results were plotted. Analyzing the simulation results, an optimum support position is obtained. Generalization was done during the normalization process.

Chapter 9. Conclusions and Recommendations

Contributions of the Report

Rapid Roadway Repair is expected to play an important role in the future during natural disasters or other catastrophic events. This report takes into consideration the fact that a mat structure would act as a temporary pavement. Therefore, precision deployment of the mat structure with predefined protocols, depending on the damage, is the key for this report. By analyzing the mat structure for different load positions, a predefined support condition and method can be proposed for a certain type of damage. Moreover, this report has given the basis for any type of damage incurred. A few changes in parameters, depending on the damage, could give another set of optimized support points.

As discussed, the primary goal of this research is to develop a good knowledge and understanding about the damages and the effective methods that can be used to overcome these situations. In order to achieve the goal, damage was defined which gaves a clear idea of what type of problem has to be solved.

In order to obtain a concept to repair the crater, a study of a conventional method is required. Rapid Runway Repair was studied, its methods, and crater profile measurement, etc. This study gives a brief idea of what concept to apply and how to personalize that concept for the road damages.

The system equations for a plate are derived with discussion about the bending of the plate structure. The detailed analysis of the plate structure is further used for modeling and simulation.

Honeycomb sandwich mats are one of the conventional mats used. Equations were derived for honeycomb mats by employing an equivalent laminate sandwich structure. This mat structure was analyzed to check whether a composite mat has the same maximum structure as a simple mat structure would experience upon loads and the results and plots obtained proved them to be similar.

Modeling and detailed simulation are discussed. A primary goal of this report is to develop the concept for RRR and optimizing the mat support conditions, which were done in the results chapter. The simulation results show the optimum position to simply support the mat on the pavement to take up loads at any point on the surface of the mat.

Recommendations

The research covered the detailed study of RRR and the structural analysis of the mat that is suggested for deploying over the crater. The procedures suggested could be further developed as to how to deploy the mat, considering the various aspects of the damage. Hence a procedure to deploy the mat and positioning it would be a recommended future work.

During an earthquake, it is the areas near the faults that get affected the most. Prior information about these regions and availability of the repair vehicles would be significant during emergency needs.

In this report, we considered the orientation of the mat with respect to the pavement to be zero. However, one might be interested in varying the orientation of the mat. Then some of the input orientation parameters have to be changed to obtain the simulation. Certainly, this would provide good results and can be used when the pavement is irregular.

With respect to a Rapid Road Repair vehicle, we conclude that a system consisting of a Trailer support structure and a Wheel Track driving surface could, along with the help of additional supports and ramps, effectively complete all the repair types, from simple cracks to complex vertical offsets with canted road surfaces. The Trailer support structure was chosen because of its ease of transportation and versatility. For many of the repair cases, wheeling the trailer up to the damage is the easiest way to complete a repair. For more complicated cases, additional ramps and multiple units can be connected. A trailer support structure takes care of the deployment and transportation, eliminating the need to design a costly specialized trailer or vehicle for deploying the repair structures. Additionally, because the repair structures are themselves trailers, any Caltrans vehicle with a towing hitch can take them into the field, allowing for multiple repairs to take place in different areas at one time.

References

Addis, William, *Structural engineering: the nature of theory and design*, New York: Ellis Horwood, 1990.

Bathe, Klaus-Jürgen, *Finite element procedures in engineering analysis*, Englewood Cliffs, N.J Prentice-Hall, 1982.

Beer, Ferdinand and Russel Johnston, Jr. Mechanics of Materials. McGraw-Hill, Inc., 1992.

Bertholet, Jean-Marie. *Composite materials : mechanical behavior and structural analysis*, New York : Springer, c1999.

Bowes, William H, *Stress analysis by the finite element method for practicing engineers*, Lexington, Mass: Lexington Books, 1975.

California Department of Transportation. Manual of Traffic Controls for Construction and Maintenance Work Zones. State of California - Business, Transportation and Housing Agency, Department of Transportation, 1990.

Chang, Shujie, *Rapid Runway Repair (RRR) Techniques: A System Analysis*, NCEL Technical Note, 1990.

Christensen, R. M, *Mechanics of composite materials*, New York: Wiley, 1979.

Cook, Robert Davis, *Finite element modeling for stress analysis*, New York: Wiley, 1995.

Federal Highway Administration. 1996 Highway Statistics. Federal Highway Administration, Office of Highway Information Management, 1997.

Jones, Robert M., *Mechanics of Composite Materials*, Hemisphere Publishing Corporation, 1975.

P3/Patran User Manuals, *Laminated Theory*, Volume 2, The MacNeal-Schwendler Corporation.

Pilkey, Walter D. Formulas for Stress, Strain, and Structural Matrices. John Wiley & Sons, Inc., 1994.

Qualification Training Package, *Crater Profile Measurement*, version 1.0, HQ Air Force Civil Engineer Support Agency, Directorate of Operations.

Rivello, Robert M., *Theory and Analysis of Flight Structures*, McGraw-Hill, Inc, 1969.

Roark, Raymond J. and Warren C. Young. Formulas for Stress and Strain. McGraw-Hill, Inc., 1975.

Shigley, Joseph and Charles Mischke. Mechanical Engineering Design. McGraw-Hill, Inc., 1989.

Shigley, Joseph and John Uicker, Jr. Theory of Machines and Mechanisms. McGraw-Hill, Inc., 1995.

Soares, Paul A., *Development and Testing of Rapid Repair Methods for War Damaged Runways*, UFL, 1990.

Topping B.H.V., *Advances in optimization for structural engineering*, Edinburgh: Civil-Comp Press, 1996.

Tseng, P.K., Clesen, S.F., Siacunco, J.P., White, W.A., Velinsky, S.A., 1997, Development of an Automated Cone Placement and Retrieval Machine, Advanced Highway Maintenance and Construction Technology Research Report: UCD-ARR-97-12-17-01

U.S.A.F Manuals, *Rapid Runway Repair,* Series 10-31,AFPAM 10-21V.pdf

Ulrich, Karl T. and Steven D. Eppinger. Product Design and Development. McGraw-Hill, Inc., 1995.

Zienkiewicz, O. C, *The finite element method*, 4th edition New York : McGraw-Hill, 1989-1991.