SPACE SHUTTLE CRAWLER TRANSPORTER TRUCK SHOE QUALIFICATION TESTS AND ANALYSES FOR RETURN-TO-FLIGHT

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Abstract

A vital element to Launch Complex 39 (LC39) and NASA's Kennedy Space Center (KSC) mobile launch transfer operation is a 3 million kilogram behemoth known as the Crawler Transporter (CT). Built in the 1960's, two CT's have accumulated over 1700+ miles each and have been used for the Apollo and the Space Shuttle programs. Recent observation of fatigue cracks on the CT shoes led to a comprehensive engineering, structural and metallurgical evaluation to assess the root cause that necessitated procurement of over 1000 new shoes. This paper documents the completed dynamic and compression tests on the old and new shoes respectively, so as to certify them for Space Shuttle's return-to-flight (RTF). Measured strain data from the rollout tests was used to develop stress/loading spectra and static equivalent load for qualification testing of the new shoes. Additionally, finite element analysis (FEA) was used to conduct sensitivity analyses of various contact parameters and structural characteristics for acceptance of new shoes.

BACKGROUND

Among the variety of operations at NASA's Kennedy Space Center (KSC) Launch Complex 39 is one that uses mobile transfer of a fully assembled Space Shuttle to the launch pad using a unique engineering mechanism known as the Crawler Transporter (CT). The CT is one of the world's largest tracked vehicles weighing around 3 million kilograms and is used to lift approximately 6 million-kilogram combination of a mobile launcher platform (MLP) plus the Space Shuttle Vehicle and transfer this load approximately 6-8 kilometers from its point of assembly inside the Vehicle Assembly Building (VAB). The CT consists of four double-tracked trucks, 3 meters high and 12 meters long. Each of the 8 tracks contains 57 shoes with each tread shoe weighing about 900 kilograms. Originally designed and built for the Apollo program in the 1960's, the two CT's have accumulated over 1700+ miles each compared to the original requirement of 100 miles. Prior work [1,2] also indicated that unique vibration characteristics of the CT are attributable to the drive mechanism, especially during rollout, whose durations can last over 6 hours. Moreover, shoe pass and tread belt mechanism are related to fundamental drive frequencies at CT nominal speed of 0.9 MPH, and could potentially lead to highest vibration conditions during the CT/MLP/Vehicle rollout to the pad.

During CT shoe inspection/refurbishment, cracks were found in many shoes, propagating from the internal cavities below the shoe roller path and related to defects in the casting. The cracks mostly originated in the short slot section of the shoe, on the top of the large cavity. Metallurgical examination of the shoe sections indicated that the observed cracks were due to fatigue phenomenon; attributable to and originating from subsurface casting defects at the time of manufacture several decades ago. A comprehensive test, structural analysis and non-destructive examination of existing shoes and rollers were then performed to identify the failure modes, assess adequacy of metallurgical requirements, and develop structural characteristics for the procurement of new shoes. Two separate types of tests, dynamic and static were planned for the evaluation of old shoes and to provide engineering rationale for the procurement and certification of new shoes.

DYNAMIC CT/MLP ROLLOUT TESTS

The Space Shuttle Vehicle (SSV), consisting of the orbiter, solid rocket boosters (SRB) and external tank (ET) undergoes periodic structural fatigue analyses as a part of the mission life certification program. The SSV, assembled and mounted on the mobile launch platform (MLP) in the VAB, is lifted and transported to the launch pad by the CT. This rollout to the pad can last in excess of 5-6 hours and imposes significant load/stress on the CT shoes. Before new shoes were procured it was vital to establish a clear understanding of the old shoe stresses and fatigue behavior, so as to provide valuable input for the specification of new shoes.

Thus, instrumented shoe tests were proposed for the CT and CT/MLP rollout configurations [3] to validate the analytical models developed to predict the shoe loads/stresses and compute fatigue life or mileage to failure for the old and subsequently the newly procured shoes. From the knowledge of CT/MLP instrumented rollout load and stress data, estimations and extrapolations were planned for the CT/MLP/Vehicle load case, since testing with the entire stack was not an option.

1. Move Operations and Test Phases

The CT consists of 4 double-tracked trucks, with each of the inside or outside tracks comprising of 57 shoes. Moreover, the load path to the shoe is through the roller and is highly dependent on shoe interaction with crawler way surface. Terrain and ground stiffness significantly influences load distribution for each shoe. Since it was critical to understand the loading of the individual shoe, it was decided to collect shoe loads with due regard to loading/contact conditions. Seven (7) separate test phases covering a variety of CT moves (forward and reverse), loading conditions (with and without MLP on top), and ground conditions (soft, rocky, and stiff) were considered. The later simulated the loading behavior as the CT moves from the CT yard (soft) to the MLP park site (crawler way with rocks), and VAB threshold (stiff with steel plate and plywood) surfaces. Strain gage data was recorded during each of the move operations and test phases as outlined in Figure 1.

2. Strain Gage Instrumentation

Two (2) shoes were instrumented for move to the VAB from the CT yard. Shoes #310 and #80 were instrumented with rosette (3 gages) strain gages, located at the center of the shoe axis just below the (short slot) large cavity. These two shoes are adjacent to each other, with shoe #310 experiencing roller loads first because of the CT movement direction. Additionally, five (5) shoes were instrumented for a move across the VAB threshold. Whereas shoes #80, #303, #240, #154, and #319 (not shown) were installed with rosette (3 gages) strain gages, shoe #310 was disconnected. Gage placement location was derived from a quick finite element analysis (FEA) to identify areas showing high stresses as the CT roller traverses across the roller path. All the gages were on CT-1 Corner C outboard belt to facilitate easy access and management of the instrumentation cables during the rollout (Figure 2).

3. Measured Shoe Stresses during CT/MLP move

Measured strains during the rollout phase of the CT/MLP move were converted to stress to compare them with finite element stress analysis results. The rollout data yielded extremely valuable results and understanding of several areas:

- Load sharing phenomenon between adjacent shoes during roller movement
- Occurrence of peak stresses and identification of roller position/loading effects
- Variation of peak stresses within each revolution of the shoe
- Assessment of roller position on shoe stress profile during rollout
- Evaluation of variation in shoe stresses attributable to the direction of CT movement
- Understanding of terrain effects on peak stresses experienced by shoes
- Estimation of maximum load on shoes for CT/MLP/Vehicle combination

Based on the evaluation of the rollout data, the following observations were noted herein. As each of the rollers traversed across shoe #310 and #80 that were adjacent to each other, shoe #310 shared the higher load. Also, a comparison of shoe stress profile for the shoes (Figure 3) showed the variation of stress with roller and terrain. This data also indicated that the highest stresses in the shoe are observed when the roller is directly above the strain gage. Typically, the peak stresses were 2-3 times higher than the mean stress when data for several revolutions of the shoe were analyzed. The forward direction yielded 2-3 times higher peak stresses than the reverse direction.

Various terrain levels during this rollout phase induced different maximum stress levels on the shoe for each revolution of shoe #80 and #310, respectively. The MLP parksite, Cross Road, and VAB threshold all showed significantly higher stresses. Minimum load (stress) on shoe #303 and #240 was observed during the VAB threshold in the reverse direction, however, shoe #154 and shoe #80 showed significantly higher stresses.

A summary of mean and maximum stresses are outlined in Table 1 for CT and CT/MLP rollout tests and estimated stresses for CT/MLP/Vehicle stack for shoes #80 and #310. Based on the data, maximum vertical loads calculated based on the maximum /minimum stress ratio referenced to nominal vertical loads are comparable (3.78 and 3.70 respectively) indicating a consistent load factor for nominal vertical loads. Additionally, estimated maximum vertical load (866 kips) and shoe stresses for CT/MLP/Vehicle case was based on an additional load factor of 1.316. It was also surmised that the maximum conditions occur approximately 2-3% of the time during move/rollout operations.

FINITE ELEMENT STRUCTURAL ANALYSIS

A NASTRAN full shoe finite element model (FEM) was developed earlier in the test program (Figure 4). The structural analysis was instrumental in identifying high stress zones in the shoe due to roller loads and aided in accurate placement of strain gages. Variety of sensitivity analysis was performed using this analytical model to understand influence of structural, contact, and loading parameters.

- Evaluations of no wear and roller path wear
- Roller loads applied along the shoe/roller interface for vertical and horizontal loads
- Distribution of the vertical load across the shoe/roller interface
- Pin loads applied along the lug interface
- Measurement and predictions of stress and safety factors for the CT/MLP load case
- Extrapolated stress and safety factors for the CT/MLP/Vehicle load case

Finite element analysis (FEA) served several purposes. First, using nominal shoe roller path thickness as measured for both long and short slots of the shoes #310 and #080, magnitude and location of the maximum stresses were identified. This facilitated placement of strain gages for dynamic CT rollout testing as outlined above. Calculated stress levels were compared to measured mean stresses for shoe #310 for wear and no wear conditions for the case of CT/MLP rollout tests (Figure 4). Shoe #310 showed higher stress than shoe #80. This was attributable to the measured thickness or the effective wear in the short and long slots. Table 2 provides the summary of mean and maximum stresses and safety factors (based on yield and ultimate strengths) for no wear and 5/16 inch wear extrapolated for the CT/MLP/vehicle (whole stack) load case.

FATIGUE ANALYSIS

Early in the testing program, it was envisioned that a structural fatigue analysis be performed so as to estimate useable remaining life of the old shoes. Since shoe #310 had the highest stresses, this was used to develop fatigue cycle/stress spectrum. Typical service loading of shoes for the CT, CT/MLP, and predicted CT/MLP/Vehicle (whole stack) assumed that the operational usage of the CT alone amounted to 50%, while the remainder of the usage was equally attributable to the CT/MLP and CT/MLP/Vehicle load cases. Fatigue analysis was then performed based on the Goodman criteria and Miner's Rule for variable amplitude loading to determine the mileage to failure. Due consideration was given to the material properties for the old and proposed new shoe. Additionally, for the case of the old shoe, effects such as notched vs. unnotched specimens during casting, shoe casting defects, low tensile strength influences, class type of shrinkage flaws and its' sensitivity on the fatigue life were considered. Table 3, based on the above analysis, highlights the estimated fatigue life to be the highest at 13762 and 10056 miles to failure for the new and old shoe, respectively. The underlying assumptions would require the casting to be sound and to meet minimum strength and metallurgical requirements under notched conditions. Effects of Class 2/6 shrinkage and effects of flaws that typically extend to the surface would drastically undermine the fatigue life and bring it to around 3090/876 respectively. The average useful fatigue life of 1983 miles is close to the 1700+ CT mileages.

STATIC COMPRESSION TESTS

The purpose of these tests was twofold. First, verification of structural integrity of the newly fabricated CT shoes was of significance. Secondly, the static test data would be used to correlate dynamic load versus strain (to serve as a calibration curve) for comparing the current and future CT rollout strain data. An existing shoe (#319) and a new prototype (ME Global #X003) were first inspected for cracks, voids, and major imperfections. Later, the shoes were instrumented by placing one (1) rosette strain gage at the center of the shoe axis below the (short slot) larger cavity. Several fixtures including the roller fixture with an equivalent spherical contour were used for test purposes [4].

Compressive loads were applied using a hydraulic ram from 0-900 kips in 100 kip increments at three separate locations across the roller/shoe interface (Figure 5). The maximum load corresponds to the estimated CT/MLP/Vehicle stack loads of 866 kips. Stresses were calculated from load test strain measurements. The finite element model was used to calculate stresses for various rollers to shoe profile to correlate with the static tests. The FE structural model allowed for estimated wear of shoe #319 (up to ~0.5 inch). Roller and shoe profiles were based on design specification and used maximum/nominal tolerance. Maximum tolerance gave best correlation to the predictions versus the compression tests. The new shoe withstood the applied compressive load.

CONCLUDING REMARKS

Recently, fatigue cracks were observed in the old shoes, mainly attributable to metallurgical and casting defects at the time of manufacture several decades ago. Over 1000 new shoes were then fabricated to refurbish the two crawlers. This paper documents recently completed dynamic tests on old shoes and static compression tests on the new shoes in order to qualify the latter for Space Shuttle Discovery's return-to-flight slated for May 2005. Measured strain data from the rollout tests is used to develop stress/loading spectra and static equivalent load for qualification testing of the new shoes. In addition, finite element analysis is used to arrive at maximum stresses in the shoe and to conduct sensitivity analysis to assess the interaction between the roller/shoe contact area, variable shoe thickness effects across the roller path, and interfacial stiffness at the shoe to ground as the CT traverses from soft to hard surfaces. The new shoes were accepted upon completion of this analytical and experimental effort for return-to-flight application.

ACKNOWLEDGMENT

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REFERENCES

1. Space Shuttle Crawler Transporter Vibration Analysis in support of Rollout Fatigue Load Spectra Verification Program, ICSV 11, St. Petersburg, Russia, (July 2004)

2. Crawler Transporter (CT)/MLP System Overview/Structural Models in support of Rollout Fatigue Spectra Analysis, NASA/USA report to NASA Loads Panel, (November 2003)

3. Crawler Transporter (CT) Tread Belt Shoe – Test Data Analysis, Structural and Fatigue Analysis Summary, NASA/KSC Internal Document, (May 2004)

4. CT Shoe LETF Load Tests Summary, NASA/KSC Internal Document, (Jan 2005)

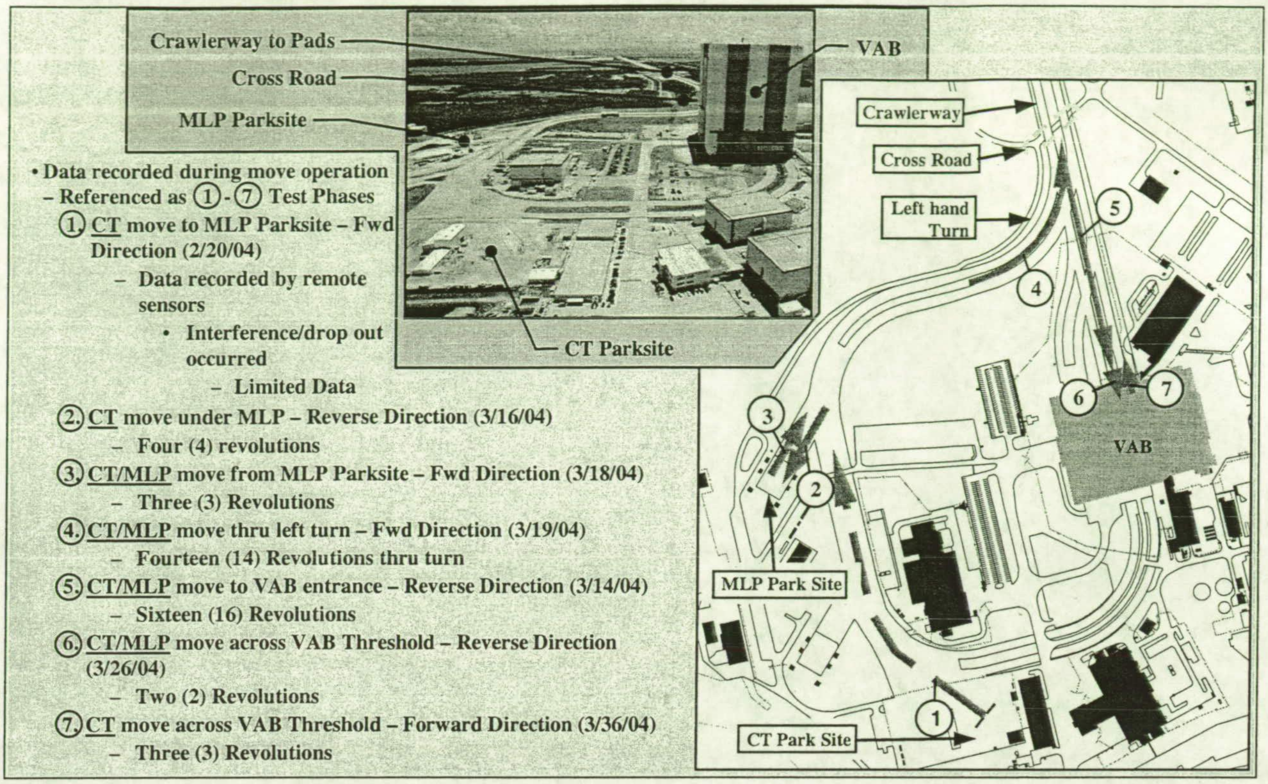

Figure 1. CT and CT/MLP Move Operations and Test Phases

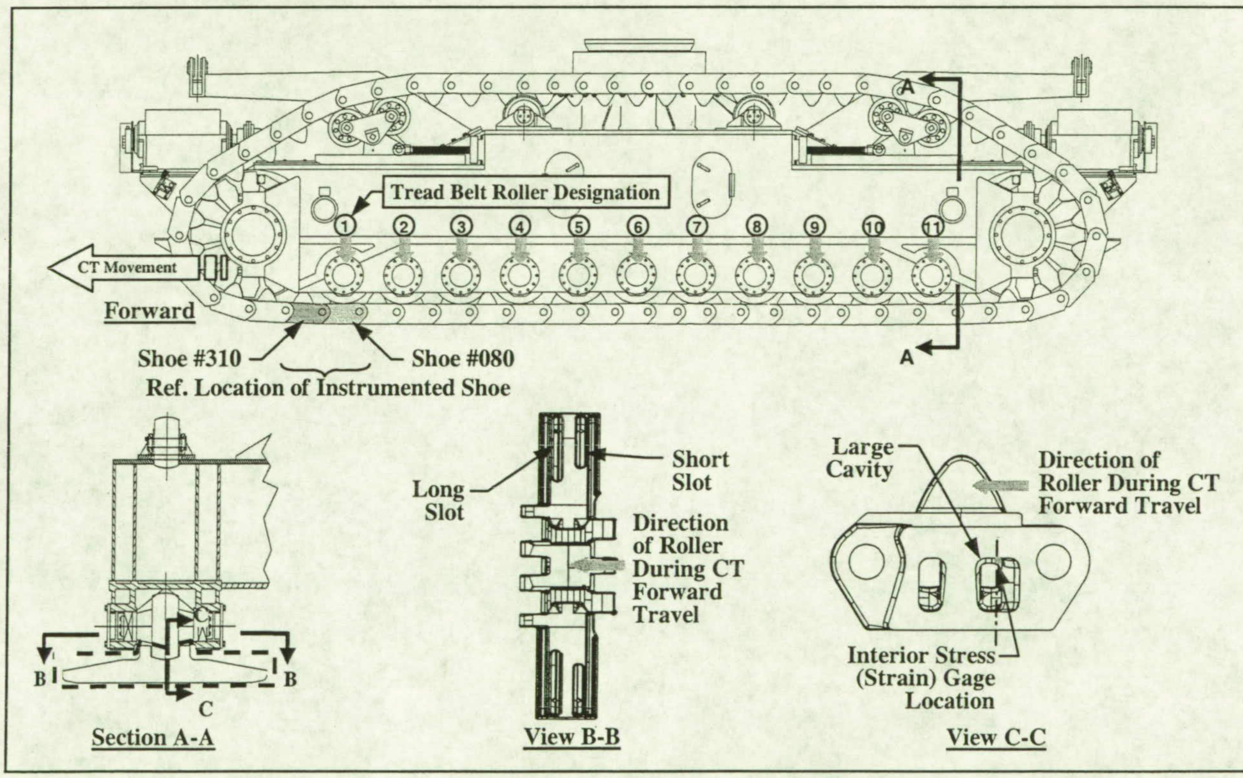

Figure 2. CT Shoe/Roller Designation and Strain Gage Location

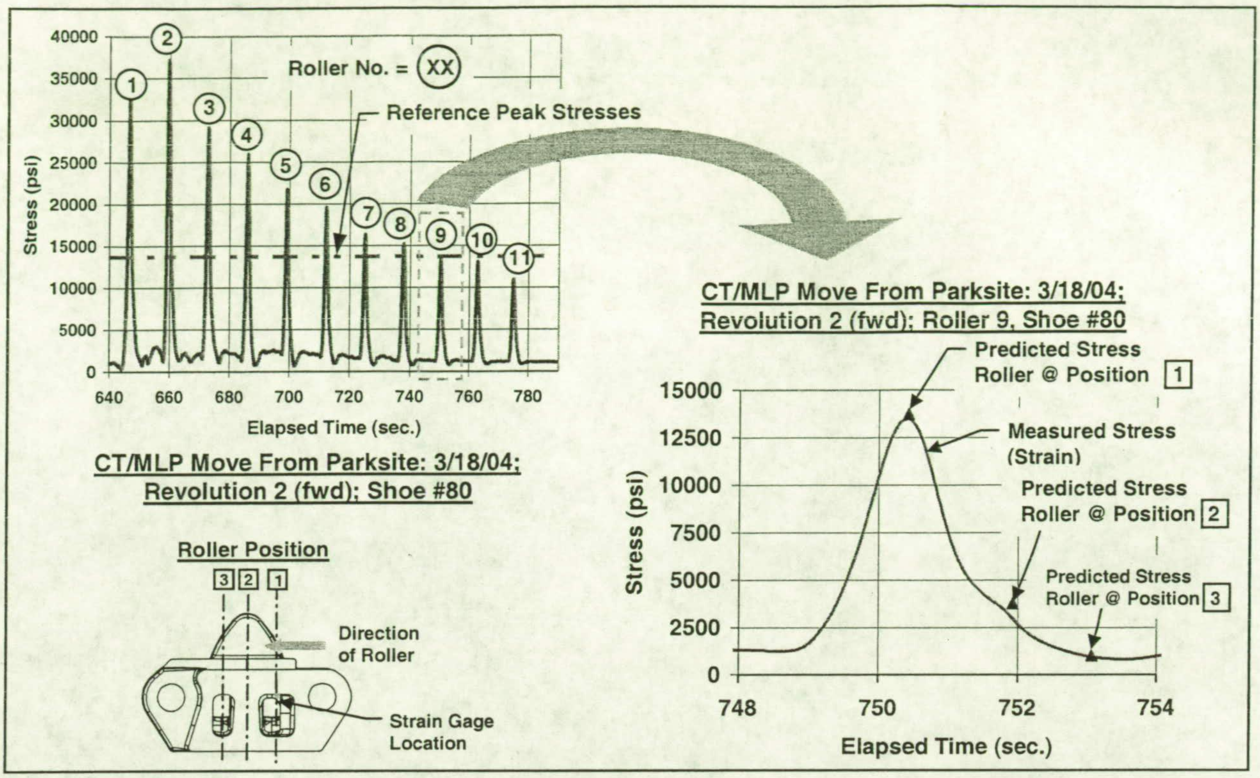

Figure 3. Shoe Stress Profile during Roller Movement over Shoe

Table 1. CT, CT/MLP, CT/MLP/Stack Test and Estimated Stresses

Operational Conditions, Loads and Shoe #080 & #310 Test/Estimated Stresses								
Operational Conditions	Vertical Load (Max.)		Shoe # 080 Stresses (ksi)			Shoe #310 Stresses (ksi)		
	Nominal	Max.	Mean Stress	Max. Stress	Max./Mean Ratio	Mean Stress	Max. Stress	Max./Mean Ratio
CT Move	72	377**	4.5	23.6	5.24	4.6	18.9	4.11
CT/MLP Move	174	658**	13.2	49.7	3.78	15.9	58.9	3.70
CT/MLP/Vehicle. Rollout*	229	**866**	17.4	65.7	--------	21	77.7	--------

*Estimated by Load Factor of 1.316 referenced to CT/MLP case

** Based on Max./Mean Ratio for Shoe #080

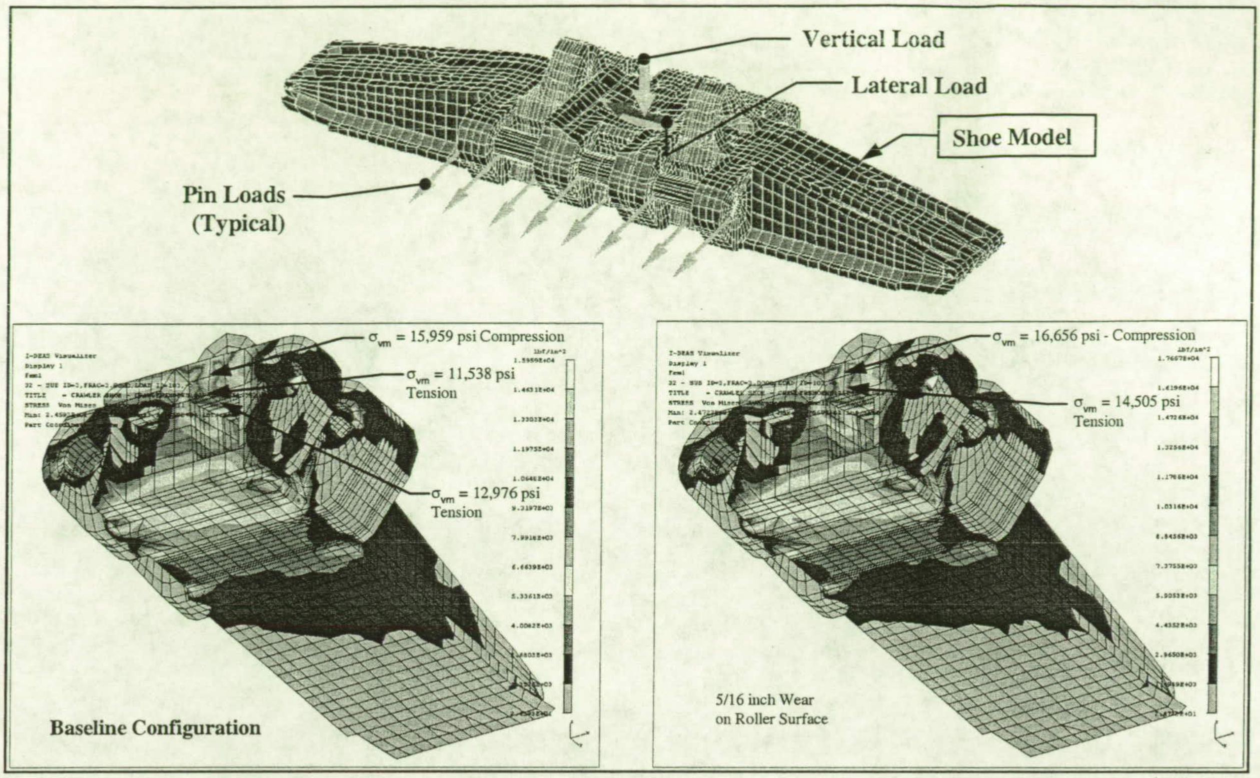

Figure 4. Full Shoe FE Model and Zone of Maximum Stress

Table 2. Shoe Loads and Mean/Maximum Stress/Safety Factors

Existing Shoe & New Shoe Stresses & Safety Factors – CT/MLP/Vehicle. Case						
Shoe Condition	Load Condition (Kips)	Stress Condition (ksi)	Existing Shoe		New Shoe	
			Yield Safety Factor*	Ultimate. Safety Factor**	Yield Safety Factor*	Ultimate. Safety Factor**
No Wear	229 (Mean)	17.1	6.4	7.6	7.4	8.1
	866 (Max.)	64.7	1.7	2	1.9	2.1
5/16 in. 'Wear'	229 (Mean)	19.1	5.8	6.8	6.6	7.3
	866 (Max.)	72.3	1.5	1.8	1.7	1.9

*Yield Safety Factor = Yield Strength/Stress

** Ultimate Safety Factor = Ultimate Strength/Stress

Table 3. Structural Fatigue Life Summary

Estimated Fatigue Life of CT Shoe Based on Material Conditions					
Item #	Component/ Condition	Material Condition/ Type of Flaws	Ultimate Tensile Strength (ksi)	Fatigue Endurance Limit (ksi)	Mileage to Failure
1	New Shoe per Min. Specification	Sound Material with Notch	138.8	38.3	**13,762**
2	Existing Shoe per Min. Specification	Sound Material with Notch	130	36.9	10,056
3	Existing Shoe with Flaws*	Class 2 Shrinkage (Extends to Surface)	130	22.1	3,090
4	Existing Shoe with Flaws*	Class 6 Shrinkage (Extends to Surface)	130	16.9	**876**
5	Existing Shoe with Reduced Tensile Strength	Sound Material with Notch	106.7	33.2	**725**

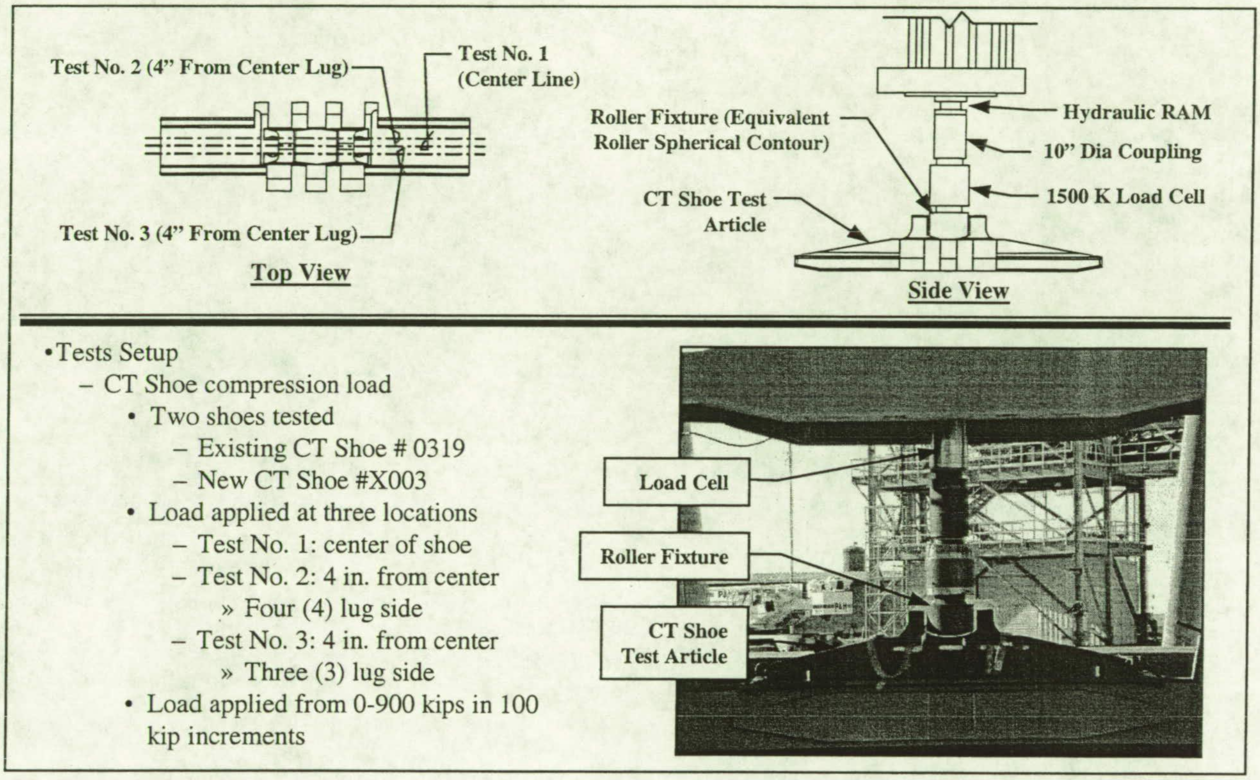

Figure 5 LETF Hydraulic Load Test Facility with the New Shoe