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Finite Element Analysis of a Knuckle and Coupler Assembly

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Summary

In an effort to improve the performance and extend the life of knuckles and couplers, the Transportation Technology Center, Inc. (TTCI) conducted an investigation to determine the working stresses and define critical stress areas in a coupler/knuckle assembly. The research conducted by TTCI is part of the Association of American Railroads' (AAR) Train Condition Monitoring Strategic Research Initiative, SRI 6D: Improved Castings and Inspection Procedures.

A nonlinear finite element analysis (FEA) of an E60EE coupler, knuckle, and pin was completed as the first step in completing a fatigue life analysis of these components. A 400,000-pound draft load was applied to the pulling face of the knuckle and all material data was based on AAR Grade E cast steel. Stress and total deformation data was recorded for several time steps in the FEA. The FEA results led to the following observations/conclusions:

- The coupler body is geometrically offset such that the pin is, initially, taking substantial loads. Also, the offset is causing uneven loading between the top and bottom lugs.
- Local yielding at the pin/coupler interface occurs due to the 400,000-pound load.
- The maximum stress in the coupler body is located at the upper lug.
- Permanent deformation in the knuckle is less than the allowed 0.03 inch (per AAR Specification M-211).
- There is no indication that applied load would result in failure of the knuckle or the coupler.

In 2010, modeling efforts include removing the geometric offset in the coupler body, adding a generic lock to the assembly, and using test data from tensile tests to quantify the influence of the offset on working stresses and to improve the overall accuracy of the model. Once the finite element models are complete, stress data will be used to conduct a fatigue life analysis of the coupler/knuckle assembly. Also, results from this research will be compared to static test data collected in 2008.

Finally, the combination of FEA results, fatigue life estimates, and research conducted to determine the current state of the tolerances in couplers and knuckles will be used to provide recommendations to the AAR Coupling Systems and Truck Castings Committee for improved standards for cast components.



INTRODUCTION

As part of an industry effort to improve the performance of coupling components, TTCI initiated a research effort to determine the current state of component tolerances and the influence of these tolerances on component stress and performance. The research conducted by TTCI is part of AAR Train Condition Monitoring Strategic Research Initiative, SRI 6D: Improved Castings and Inspection Procedures.

BACKGROUND

The objective of SRI 6D is to improve the safety, quality, and performance of cast components by reducing the number of failures occurring in service. TTCI developed a program that focuses on three areas to achieve the project objectives:

- Component life
- Inspection and defect detection
- Interchangeability and tolerances

Each one of these areas encompasses many aspects of the design and quality of cast components. This *Technology Digest* (TD) details the analysis approach, results, and future work focused on improving the life of cast components. Additional TDs are available that summarize the activities and results relating to the two other focus areas of SRI 6D.^{1,2}

INCREASED COMPONENT LIFE

Between 2000 and 2008, over 80,000 knuckles and 56,000 couplers were removed from service because they were either broken or cracked.¹ Although the exact age of each of these components is unknown, most of the removals occurred before the target life of the component was reached. As part of SRI 6D, TTCI has developed a methodology aimed at improving the performance and increasing component life for castings. Figure 1 is a flowchart that details the research approach that will be used to achieve better performing castings.

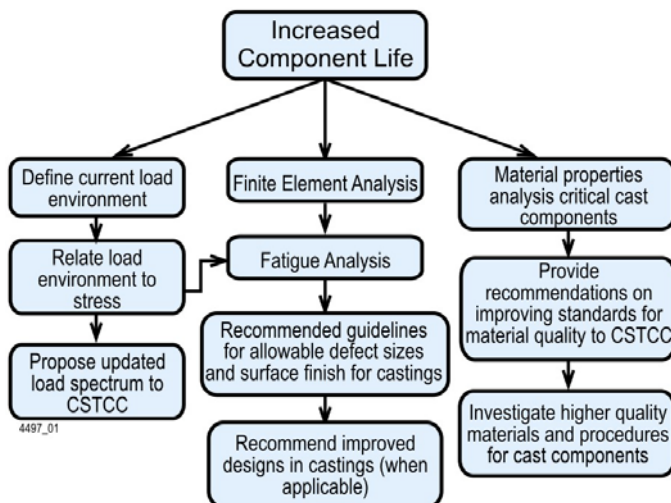


Figure 1. Increased Component Life Flowchart

To increase component life, TTCI will define current load and operating environments, conduct finite element and

fatigue analysis to determine the expected life of the components under the current operating conditions, and research the quality of materials used in castings to determine if metallurgy changes will improve the durability of cast components. At the conclusion of this research, TTCI would like to provide the AAR Coupling Systems and Truck Castings Committee with an updated load spectrum, recommendations on allowable defect sizes and improved designs (if necessary), and a summary of metallurgical properties that have the potential to improve the performance of cast components.

FINITE ELEMENT ANALYSIS APPROACH

The FEA determined the working stresses in the knuckle and coupler under draft load conditions and defined critical areas of stress in the knuckle and coupler.

Development of the finite element model was completed in several steps. First, solid models of the knuckle and coupler were generated using laser scanning techniques. Next, the models were meshed, boundary and loading conditions were applied, and material properties were defined. After all of the inputs were established, the model was evaluated and the stress and deformation results were summarized. Finally, the results from the FEA were compared to results from the static testing completed in 2009.

FINITE ELEMENT ANALYSIS INPUTS

Solid models were generated for an E60EE knuckle and coupler assembly by a third party laser-scanning consultant. The external surfaces and internal coring of each of the bodies were scanned. Once point clouds were generated for each of the parts, a three-dimensional computer-aided design model was created and inserted into ANSYS® for meshing and application of restraints and loads.

Mesh

The geometry was meshed with nonlinear element types to more appropriately simulate the physics of the material properties, allowing greater confidence in any calculated plastic stress due to large tensile loads. The model was meshed with more than 180,000 quadratic brick and tetrahedral elements. Figure 2a shows the mesh density of the entire model. Additional refinement, shown in Figure 2b, was necessary at the high stress areas to better capture the local stress state in the parts.

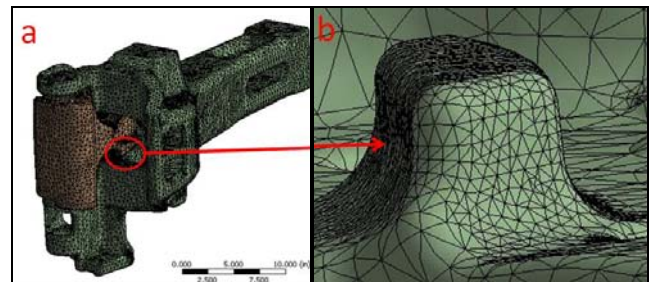


Figure 2. Mesh Density Used for Finite Element Model

Material Properties

The following material properties for AAR Grade E cast steel were used as inputs for the simulation:

- Elastic Modulus – 30E6 psi
- Poisson’s Ratio – 0.29

The bilinear kinematic hardening rule was used to establish a stress strain curve for the analysis, because test data was not available at the time. The pin was modeled using linear properties of a medium carbon steel to reduce the processing time of the model.

Boundary Conditions and Loads

Boundary conditions and load application were modeled as closely as possible to revenue service applications. Figure 3a shows the locations of the restraints and loads applied to the assembly. The back of the key slot in the shank of the coupler was fixed in all degrees of freedom. Frictionless supports were added to the top and bottom of the pin and also at the lock face of the knuckle to stabilize the model. A 400,000-pound draft load was applied at the pulling face of the knuckle. Figure 3b shows the contact elements used at several of the interfaces between the knuckle, pin, and coupler bodies. Contact elements were used at the pin hole, pulling lugs, and the interface between the hub of the knuckle and the coupler.

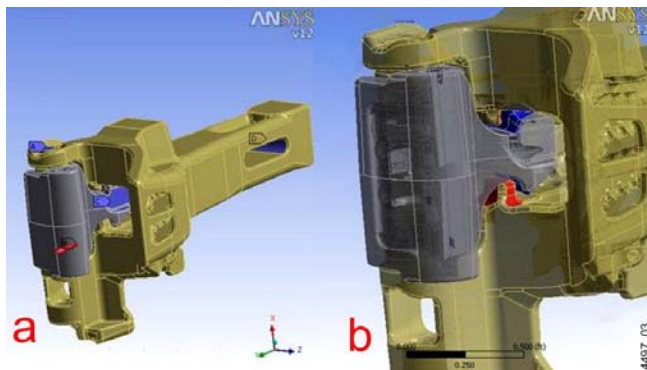


Figure 3. Boundary, Load, and Contact Conditions applied to Knuckle and Coupler Assembly

The 400,000-pound load was applied in steps to reduce run time and improve the stability of the model. Once all of the inputs were added to the model, the simulation was run and results for the stress and deformation were analyzed.

FINITE ELEMENT ANALYSIS RESULTS

Von Mises (equivalent) stress, maximum principal stress, and total deformation values were recorded for each of the time steps in the analysis. Review of the individual load step data revealed that uneven lug engagement was occurring. An investigation into the cause of the uneven loading revealed that a geometric offset existed between the upper and lower pin hole bores of the coupler body. The total offset, shown in Figure 4, is approximately 0.125 inch. Review of the scan data and the part proved that the offset does exist in the part, so no modifications were made to the model.

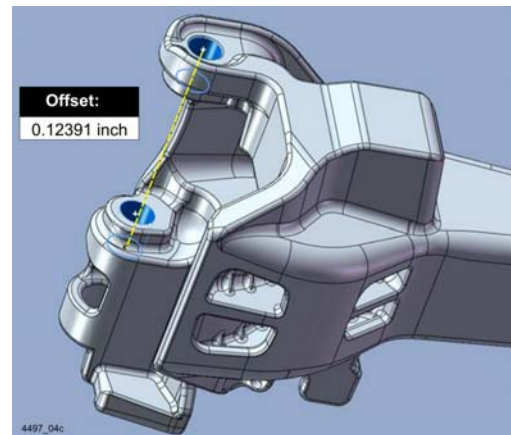


Figure 4. Geometric Offset between Upper and Lower Pin Hole Bores in the Coupler Body

As a result of the offset between the coupler pin hole bores, the pin and pin hole experience extremely high stresses near the beginning of the load application. Figure 5 shows a series of plots throughout the duration of the load application. Figure 5a is near the beginning of the load application and Figure 5d is at the final time step with full load application.

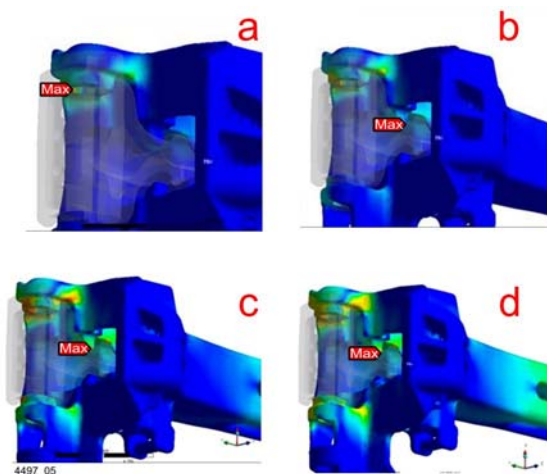


Figure 5. Coupler Body Stress Plots throughout Load Cycle

Near the beginning of load application (5a), the maximum equivalent stress is nearly 105 ksi at the pin/pin hole bore interface. As the load application continues, the load is transferred from the pin hole to the upper lug and finally to the lower pulling lug. At full load application, the maximum equivalent stress of 126 ksi is at the upper pulling lug of the coupler body. Coupler body stress values indicate that local yielding does occur and is most likely caused by the uneven lug loading condition.

Also, the results of the simulation were scoped to review knuckle stress and total deformation. The stress behavior in the knuckle followed the same pattern as the coupler body, because of the uneven loading condition. When full load was applied, the maximum equivalent stress, 146 ksi, was located at the corner of the lock interface. The concentrated stress at this location is most likely due to the restraint conditions of the model; therefore, stress levels were not considered critical at this time.

Other locations on the knuckle also exhibited stresses above the yield of the material. Maximum equivalent stress in the throat of the pulling face is between 95 and 110 ksi. Figure 6 is a stress plot of the knuckle at full load application.

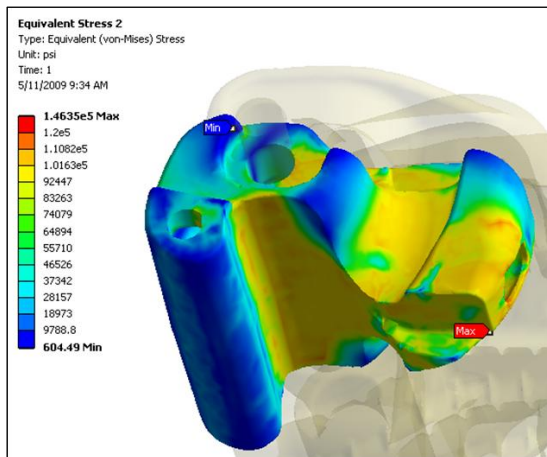


Figure 6. Knuckle Stress Plot at Full Load Application

At the end of the simulation, the assembly was returned to a zero load condition, and the permanent deformation in the knuckle was measured. An arbitrary point on the lock face was used for a reference point for all deformation measurements. Figure 7 shows the maximum permanent deformation of 0.191 inch measured between the point on the lock face and the lower radius of the pulling face.

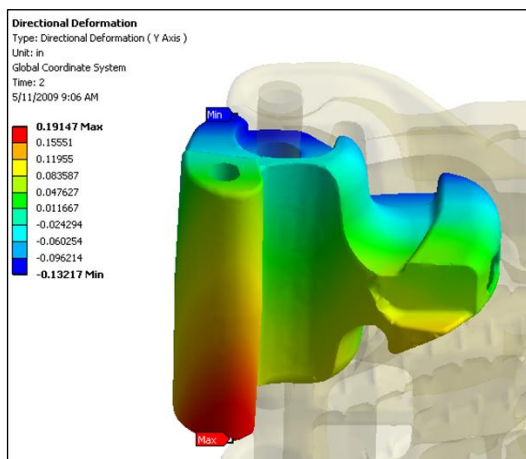


Figure 7. Knuckle Total Deformation

CONCLUSIONS

A nonlinear finite element analysis of an E60EE coupler, knuckle, and pin was completed to define critical stress areas and determine the working stresses in each of the components in the assembly. A 400,000-pound draft load was applied to the pulling face of the knuckle. All material data was based on AAR Grade E cast steel. Stress and total deformation data was recorded for several time steps in the analysis. The results from the analysis were reviewed and the following observations/conclusions were made:

- The coupler body is geometrically offset causing substantial loading in the pin and uneven lug engagement.
- Local yielding at the pin/coupler interface occurs due to the 400,000-pound load.
- The maximum stress in the coupler body is located at the upper lug.
- Permanent deformation in the knuckle is less than the required 0.03 inch (per AAR Specification M-211).
- There is no indication that applied load would result in failure of the knuckle or the coupler.

FUTURE WORK

Additional simulations are necessary to determine stress levels in the components when the lugs are engaged evenly. TTCI is modifying the finite element model to remove the offset in the coupler body and repeat the analysis described in this summary. In addition to removing the offset, a generic model of the lock will be added to improve the accuracy of the stresses at the lock interface. Finally, the bilinear kinematic curve will be replaced with a stress-strain curve developed from tensile test data of AAR Grade E cast material. Once the results from the updated FEA are processed, they will be used to estimate the fatigue life of each of the components in the assembly.

Additional research under SRI 6D is in process to determine the current state of the tolerances in couplers and knuckles. TTCI plans to use data collected from both of these efforts to improve the AAR standards and ultimately the performance of cast components. The results of all of the SRI 6D efforts will be published in a combination of TDs and AAR research summaries.

ACKNOWLEDGEMENTS

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