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Stress Analysis of a Knuckle/Coupler Assembly

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Summary

As part of an industry effort to improve the performance of coupling components, Transportation Technology Center, Inc. completed a program to define critical areas of stress in a knuckle/coupler assembly under a draft load and to estimate the level of stress concentration that can be expected due to a limited set of surface defects.

Increased draft load capacity for the knuckle/coupler system could be achieved through a combination of design changes and modifications to material properties. Stress levels in the pulling lugs may be decreased significantly with changes in shape that would not affect the basic knuckle/coupler function. Increases in material yield properties would have to be pursued with care so that ductility and fatigue properties are not negatively impacted.

Results of the finite element analysis (FEA) indicate that if the knuckle pivot pin holes and pulling lugs are not located properly, within relatively tight tolerances, the paths by which loads are transferred from knuckle to coupler will deviate significantly from the originally designed paths.

FEA results also indicate that peak stress in a coupler/knuckle assembly may exceed material yield at a draft load as low as 250,000 pounds. Estimated fatigue life significantly decreases for each of the components when defects are present in areas of high stress.

To validate the results of the FEA and gain more knowledge about the stress state in a typical knuckle/coupler assembly, a full-scale pull test was also conducted using knuckles and a coupler of the same design for which the finite element model was created.

Results from the static testing and the FEA calculations both indicate that one manufacturer's knuckle and coupler exceed material yield in several areas of the assembly at 430,000 pounds or less draft loads. At a draft load of 430,000 pounds, there are at least four locations on the knuckle and coupler where local material yield is indicated. There are two locations where local material yield is indicated at a draft load of 390,000 pounds.

Results also show that all but one of the areas on the knuckle and coupler identified by the FEA as having high strain/stress levels under draft load demonstrated relatively high strain and stress during the strain gage testing. The most variation between the FEA and the static testing was observed in the magnitudes of stress levels. The magnitudes were slightly higher in the FEA model than during the static testing.

Additional research is ongoing to conduct a complete fatigue analysis (until crack initiation) for the manufacturer discussed here, and also a repeat of the FEA and fatigue results for a second manufacturer. Results from each of these studies will be documented in future *Technology Digests*.

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INTRODUCTION

As part of an industry effort to improve the performance of coupling components, the Transportation Technology Center, Inc. (TTCI) initiated a research effort to investigate the current stress environment for an E-type knuckle/coupler assembly. A key objective was to determine the effects of surface defects in critical areas on the fatigue life of the castings.

This research, conducted by TTCI, is part of the Association of American Railroads' (AAR) Train Condition Monitoring Strategic Research Initiative: Improved Castings and Inspection Procedures. The research was performed to improve the safety, quality, and performance of cast components by reducing the number of failures occurring in service.

PROCEDURES

The analysis covered in this digest is a continuation of work reviewed in TD-10-016,[1] which reported on results from an initial FEA with a model that had a 0.125-inch geometric offset between the upper and lower knuckle pin-hole bores in the coupler.

A second model was developed by first making a copy of the solid geometry of the first model and then installing a lock with elastic properties in the proper position. In previous models, the aft end of the knuckle had been reacted against zero deflection restraints instead of an elastic lock. In subsequent steps, the knuckle pivot pin holes in the coupler were aligned and there were extra efforts made to assure that the gaps between the knuckle and the top coupler pulling lugs were essentially the same as for the bottom lugs when the knuckle was in the closed or working position.

The geometry for the revised model was again meshed using elements with nonlinear material properties to more appropriately simulate both the elastic and plastic physics of the castings and to allow greater confidence in any calculated strain due to large tensile loads. The basic model was meshed with more than 180,000 Solid186 quadratic brick and tetrahedral elements. When surface defects were introduced, the element count increased to over 200,000. Figure 1a shows the mesh density of the entire model. Additional refinement, shown in Figure 1b, was necessary at the high stress areas to better capture the localized stress.

The bilinear kinematic hardening rule was used to establish a stress strain curve for the analysis. Material yield was set at 100,000 psi (AAR Grade E). The knuckle/coupler pin, however, was modeled using linear properties of a medium carbon steel to reduce the processing time of the model.

Boundary conditions and load application were modeled as closely as possible to revenue service conditions. A draft load of up to 450,000 pounds was applied at the pulling face of the knuckle. Contact elements or surfaces were used at several of the interfaces between the knuckle, pin, and coupler bodies. Such contact elements were used at the pin hole, pulling lugs, and the interface between the knuckle, the lock, and the inside surface of the coupler. Use of these contact elements that allow transfer of compression force between two mating surfaces but also allow the surfaces to "pull away" from each other was a critical component of this model. Figure 2 shows the ANSYS® Workbench™ finite element model with contact surfaces highlighted (red & blue surfaces) and the lock in place.

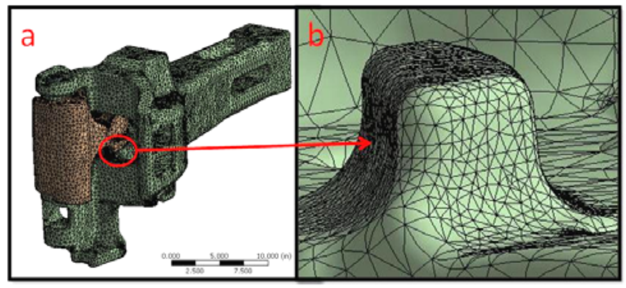

Figure 1a&b. Typical Element Mesh

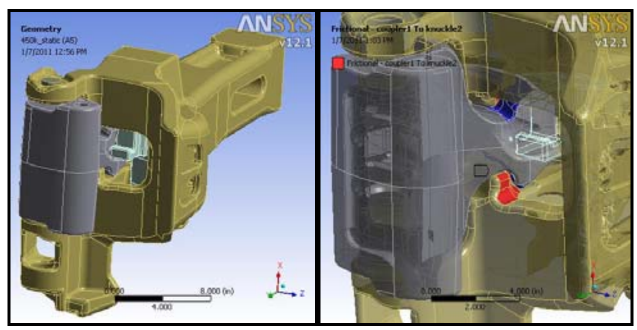

Figure 2. Example of Contact Surfaces in Model

In addition to the finite element (FE) model, a full-scale pull test was conducted using knuckles and a coupler produced by one manufacturer. Single element strain gages or rosettes were installed at 14 locations on the knuckle and coupler. Gages were placed in locations of high stress or good sensitivity of strain to load as indicated by the FEA results[1] (see Figures 3 and 4). Draft loads of up to 450,000 pounds were applied to the knuckler/coupler assembly in controlled steps using TTCI's simuloader. This fixture allows the draft loads to be applied using a mating knuckle and coupler, as Figure 5 shows. Strain data was recorded from all gage locations continuously as draft load was applied. A calibrated load cell in series with the mating coupler allowed the continuous recording of applied draft load during the test. Testing with two different knuckles installed in the same coupler was completed in an effort to detect any significant differences in load and stress distribution due to knuckle-to-coupler casting fit.

Figure 3. Strain Gages Installed on Coupler

Figure 4. Strain Gages Installed

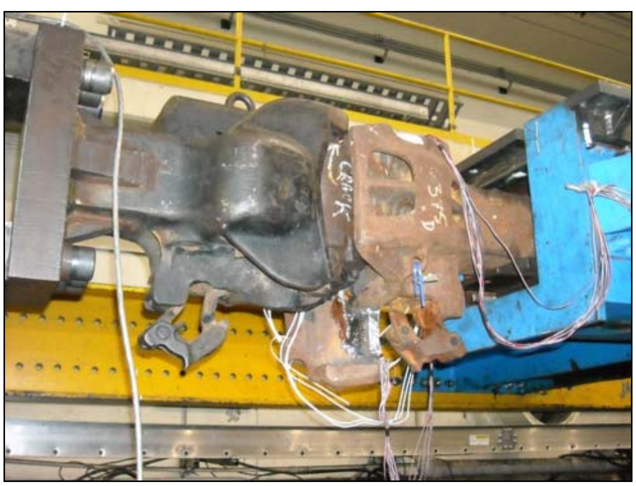

Figure 5. Draft Load Applied to Knuckle

At the conclusion of the static testing, stress results from the testing were compared to the FE model to validate stresses calculated by the model. All but one of the areas on the knuckle and coupler identified by the FEA as having high strain/stress levels under draft load demonstrated relatively high strain and stress during the strain gage testing. Differences could have been due to gages being slightly off in placement or load transfer from the knuckle to the coupler that was not exactly as modeled. The magnitudes of stress levels measured in critical areas varied slightly from the values calculated by the FEA. For example, on the side of the upper pin support of the coupler, maximum principal stress values calculated by the finite element analysis were about 20 to 25 percent higher than measured during the strain gage test.

Load placement would likely influence peak stress levels in the knuckle and coupler. As an illustration of the variability built into this kind of casting assembly, the stress values measured at the top surface of the first knuckle tested were approximately 20 to 25 percent higher than those measured on the second knuckle, even though they are similar castings.

As a result of the variability between the model and static test results, best engineering estimates for stress were used to calculate fatigue life for the manufacturer's assembly.

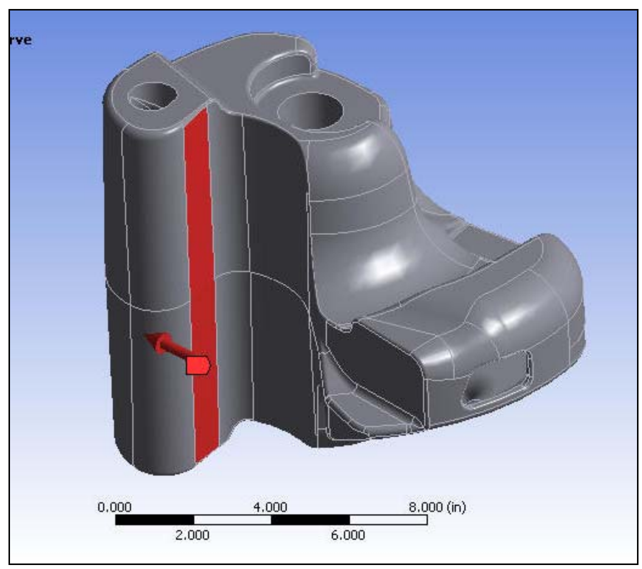

Figure 6. Application of Load on Knuckle

RESULTS

The FEA indicates that if knuckle pivot pin holes and pulling lugs are not located properly, within relatively tight tolerances, the paths by which loads are transferred from knuckle to coupler will deviate significantly from the originally designed paths. The FEA indicated that peak stress in a coupler and knuckle may exceed material yield at a draft load as low as 250,000 pounds.

The FEA shows that for a limited number of surface defect types located in areas of high stress, the maximum stress concentration factors (Kt) are on the order of 1.2 to 1.35. Test data and FEA calculations both indicate that portions of the manufacturer's knuckle and coupler exceed material yield at the highest draft load conditions possible.

Recently recorded railroad revenue service environmental load data indicates draft loads from 340,000 pounds to 430,000 pounds do occur with some regularity. At a draft load of 430,000 pounds there are at least four locations on the knuckle and coupler where local material yield occurred. There are two locations where local material yield occurred at a draft load of 390,000 pounds. Such localized yielding does not necessarily mean that failure is imminent, but it can result in a redistribution of reaction forces in the coupler/knuckle system, as Figures 7 and 8 show. This change in load distribution would again likely lead to forces that are applied to the structures that are significantly different from originally designed.

Increased draft load capacity for the knuckle/coupler system could be achieved through a combination of design changes and modifications to material properties. Stress levels in the pulling lugs may be decreased significantly with changes in shape that would not affect the basic knuckle/coupler function. Increases in material yield properties would have to be pursued with care so that ductility and fatigue properties are not negatively impacted.

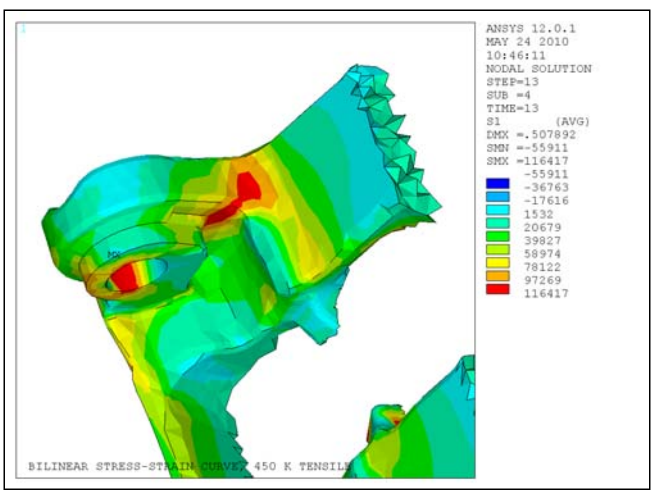

Figure 7. Stress Distribution, Revised Model

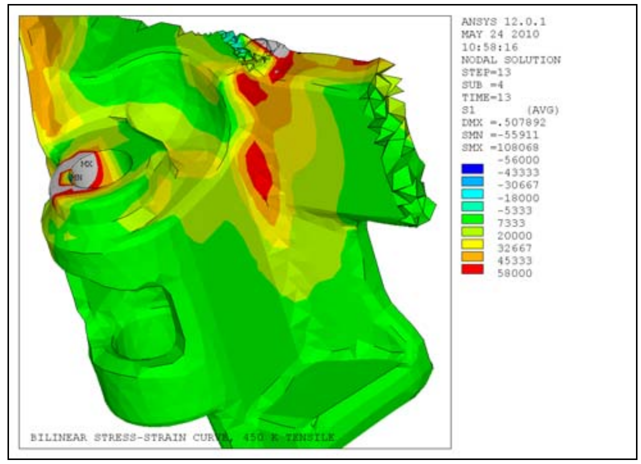

Figure 8. Stress Distribution, Revised Model

ONGOING AND FUTURE WORK

The work presented in this TD will be used in conjunction with additional research under the Strategic Research Initiative Program to propose an improved performance coupling system. The approach is as follows:

- Develop finite element models of representative components and determine high stress areas
- Determine the current state of tolerances by conducting a dimensional distribution analysis of representative castings
- Develop guidelines for improved tolerances of the components using finite element models to define acceptable stress levels in the components

At the conclusion of the program, TTCI will propose acceptable tolerances to the Coupling Systems and Truck Castings Committee for implementation in the AAR's *Manual of Standards and Recommended Practices.*

REFERENCES

1. Gonzales, Kari and Daniel Carter. May 2010. "Finite Element Analysis of a Knuckle and Coupler Assembly." *Technology Digest* TD-10-016. Association of American Railroads, Transportation Technology Center, Inc., Pueblo, Colorado