TECHNOLOGY DIGEST

TD-09-016
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TIMELY TECHNOLOGY TRANSFER

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Interim Results of Finite Element and Fatigue Analyses of Bolsters

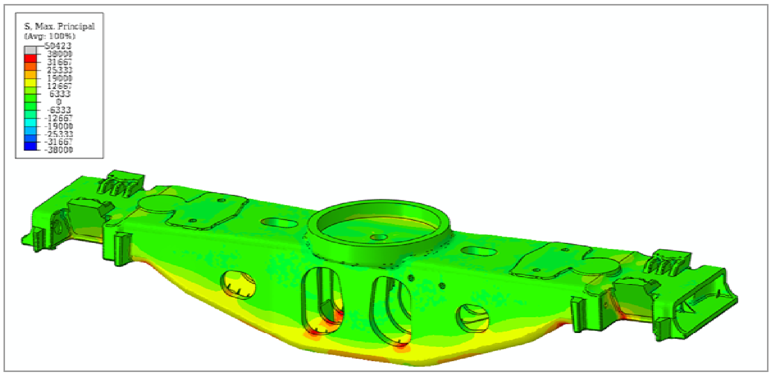
Kari Gonzales, Kevin Koch, and Daniel Carter

Summary

Between 2000 and 2008, approximately 15,000 bolster and side frame have been removed from service, because they were cracked or broken, as reported in the Association of American Railroads' (AAR) Car Repair Billing database. These failures are extremely costly in train delays and lost commodities. In an effort to reduce the number of derailments caused by failed cast car components, Transportation Technology Center, Inc. (TTCI) has conducted finite element and fatigue analyses of bolsters and side frames to help identify critical stress areas. Once the critical areas of stress are determined, defects will be simulated in critical areas to develop estimates of the allowable defect sizes for each area of the castings.

Preliminary results from the finite element and fatigue analyses indicate that bolsters that do not contain defects have infinite life for the current stress environment. TTCI plans to conduct small-scale fatigue tests to produce stress and strain life curves for bolsters. Based on data from these tests, adjustments will be made to the stress and strain life curves in the fatigue analysis and may have an influence on the current results. Finite element and fatigue analyses are ongoing for bolsters and side frames with and without defects.

In addition to determining the critical areas and allowable defect sizes in the castings, TTCI plans to develop nondestructive testing techniques to inspect for defects in the critical areas shown in red and orange in the figure below. These techniques will be designed for use as preventive maintenance measures during in-shop inspections of the car components. The developed techniques will have the potential to greatly reduce the number of in-service failures of bolsters and side frames due to the presence of casting defects.



Follow-on reports will detail the results of each of these analyses. TTCI expects to produce recommended guidelines for allowable defect sizes to the AAR Coupling Systems and Truck Castings Committee in late 2009 or early 2010.

Please contact **Kari Gonzales (719) 584-0723** with questions or concerns regarding this *Technology Digest.* E-mail: kari_gonzales@aar.com.

INTRODUCTION

Between 2000 and 2008, approximately 15,000 bolster and side frame failures have been reported in the AAR Car Repair Billing database. These failures are extremely costly in train delays and lost commodities.

In an effort to reduce the number of failures of cast car components, TTCI is conducting analyses to determine acceptable working stresses of cast car components. As a supplement to the mathematical models, large-scale laboratory tests have been performed on each of the component types.

Based on the results of the finite element analysis (FEA) and the fatigue analysis, TTCI will define critical areas and also make recommendations on tolerable defect sizes in these locations that will not compromise the strength or fatigue performance of the bolster or side frame.

In addition to determining the critical areas and allowable defect sizes in the castings, TTCI plans to develop nondestructive testing techniques to inspect for defects in the critical areas. These techniques will be designed for use as preventive maintenance measures during in-shop inspections of the car components. The developed techniques will have the potential to greatly reduce the number of in-service failures of bolsters and side frames due to presence of casting defects.

The work described in this *Technology Digest* (TD) has been completed under the guidance of a railroad sponsored consortia and AAR's Strategic Research Initiatives Program.

Finite Element Analysis Approach

A global-local modeling FEA approach was used to provide accurate stress predictions in the bolster and side frame. A full-global model was used to define the proper deformation and identify critical areas of stress. These areas were then used to define local models that capture the stress state in the identified critical areas. The local model is a section of the global model with a greater element density. The displacement fields defined in the global model edges were used as boundary conditions in the local analysis.

The information contained in this TD will focus only on the global analysis completed for the bolster when no defects were present. A short description of the approach for the addition of defects is included in the Future Work section of this TD. Follow-on reports also will be generated to describe the methods used and a summary of the results obtained for the local analyses for each of the components.

Finite Element Global Analysis Description

Solid models of three bolster designs were generated for use in a FEA model. All models were built from S-2-HD castings. Material grade was either B or B+ depending on the manufacturer of the cast component.

Using Abaqus FEA, a fine mesh was generated for all three solid models. In general, each of the models consisted of over 2-million solid elements with mid-side nodes. Figure 1 displays the mesh density used throughout this analysis.

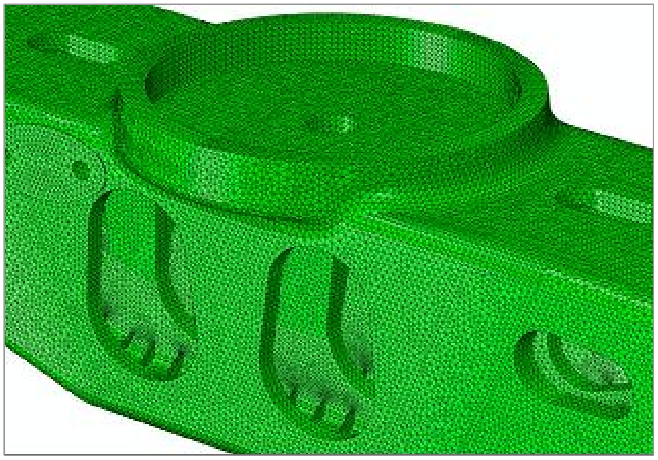


Figure 1. Sample of Mesh Density Used for Analysis

Boundary and load conditions were applied to each bolster after an acceptable mesh was generated. Figure 2 shows the restraints and load locations applied to the bolster.

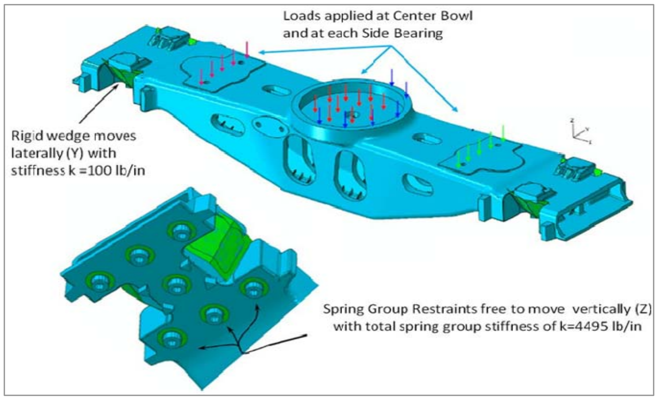


Figure 2. Restraints and Load Application Points for Bolster

Individual springs with appropriate spring rates were used at each spring location for the bolster. The top of the springs were allowed to rotate freely about the global X and Y axes. Contact elements were used between the top of the spring and the bottom of the bolster. The following load cases were applied to each of the three bolsters.

- Load Case 1: 312,500-pound center bowl load, plus 10,000 pound loads on each side bearing
- Load Case 2: 250,000-pound center bowl load, plus 50,000 pound load on one side bearing and no load on the opposite side bearing
- Load Case 3: 187,500-pound center bowl load (on the bowl edge), plus 80,000 pound load on one side bearing and no load on the opposite side bearing

Each of the solid models were restrained and loaded in the same manner so that the results could be directly compared and the general areas of critical stresses could be defined.

Finite Element Analysis Results – Bolster No. 1

The results from the FEA indicate that there are two critical areas for the S-2-HD type castings. Figure 3 is a stress plot for Load Case 1. The two critical stress areas are shown in red/orange colors and are located in the transition area near the spring seat and in the brake rod holes.

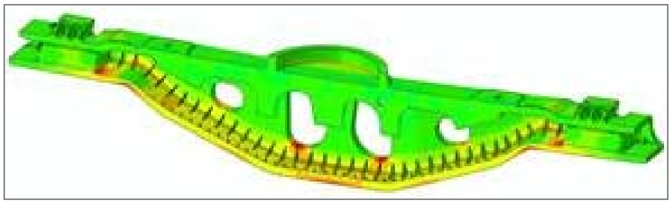


Figure 3. Sample Stress Plot Showing Critical Areas

Table 1 is a sample of the results obtained from the FEA for the stress at the brake rod holes for all bolsters. Additional details for Bolster 1 and the results for Bolsters 2 and 3 will be available in follow-on reports.

Table 1. Maximum Principal Stress at Brake Rod Hole

Bolster	Load Case	Maximum Principal Stress at Brake Rod Hole (ksi)
1	1	36.7
1	2	31.7
1	3	31.0

Table 1 shows that the maximum principal stresses in the brake rod hole are approximately 60 percent of the yield strength (50 ksi) of Grade B+ material. Load Case 1 is the most severe and produces the highest stresses at the brake rod hole. Because Load Case 1 is very severe, the number of cycles these load events actually occur must be quantified and accounted for in the fatigue analysis.

Fatigue Analysis – Bolster No. 1

A stress-life based fatigue analysis has been completed for Bolster 1. The load environment data used in the analysis was taken from dynamic center bowl and side bearing transducers mounted on an aluminum coal hopper car operated in unit train coal service collected between 2006 and 2007.

The total mileage of recorded over-the-road data is 8,480 miles. During the accumulation of the mileage, the hopper car was loaded to the rated 286,000-pound gross rail load. The maximum dynamic center bowl and side bearing loads recorded during this time were 280,000 pounds and 85,000 pounds, respectively.

Key assumptions made in conversion of load environment histograms to the stress environment histograms for the fatigue analysis are as follows:

- Center bowl load cycles ranging from less than 130,000 and to 135,000 and above are considered pitch or bounce cycles (only where side bearing loads do not vary significantly from static values).
- When either side bearing load has a maximum value above 30,000 pounds and a minimum load of 10,000 pounds or less, it is considered a roll motion event.
- Center bowl load actually decreases as side bearings are loaded above 30,000 pounds (the relationship between center bowl load and side bearing load can be determined by inspecting time domain data).
- The number of events containing a combination of roll and pitch or bounce motions are relatively small and do not contribute significantly to fatigue damage at the two locations inspected.

Relationships between bolster load and nominal stress at the two critical locations were determined by inspection of the FEA results. Stress-life was estimated at the two critical areas specified for the bolster. The first area is at the bottom of the brake rod hole. The second area is in the transition (near the springs) on the bottom surface of the casting where the casting depth changes significantly. These load and nominal stress relationships allowed for the conversion of center bowl and side bearing load histograms to a single range-mean stress histogram.

The stress-life (S-N) curve was derived from specimen fatigue data.[1] The tests were completed under reverse bending (R=-1) using Grade B cast material, including the as-cast surface. As a result, effects of surface finish and the presence of small pits or inclusions were accounted for in the curve development, but the effects of major defects, material size, or loading condition were not included. The S-N curve was modified to account for the effects of specimen size and load type (bending versus tensile-tensile). Figure 4 shows the original and modified curves.

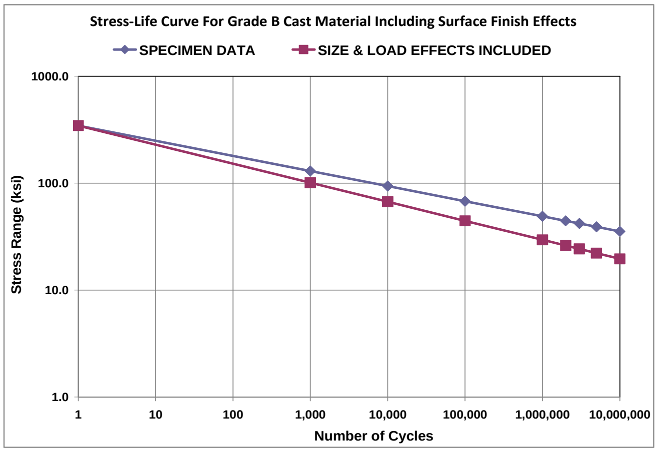


Figure 4. Stress-Life (S-N) Curve used for Fatigue Analysis

The stress-life analysis uses a more conservative approach for fatigue life estimation because it assumes that the S-N curve has a constant slope for all ranges of life. As a result, all stress ranges, regardless of how small, create some amount of fatigue damage.

Using the previously stated condition, the completed fatigue analysis indicates that Bolster 1 has an infinite life, with the lowest estimated life at over 32-million miles. Comparing the two high stress locations, fatigue damage in the transition area is estimated to be approximately 4.8 times greater than that in the brake rod hole.

Full-Scale Fatigue Test Results

TTCI completed full-scale dynamic fatigue testing on one bolster and three side frames. Testing was conducted in accordance with the AAR's *Manual of Standards and Recommended Practices*, M-202 for bolsters and M-203 for side frames, to determine the influence of surface anomalies on the fatigue life of large cast components.[2]

All castings were inspected using dry magnetic particles (MP) before testing. Indications on the side frames and bolster consisted of linear indications, scabs, pits, and gouges. Figure 4 is a collage of photographic documentation highlighting some of the surface irregularities found during MP inspection.

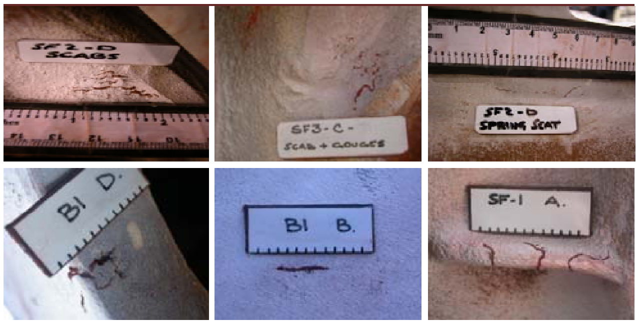


Figure 4. Photographs of Several Indications Found During Initial Inspection of Test Castings

Each of the castings had multiple indications in various critical regions. All of the indications in the critical regions were monitored during testing using dry MP and/or liquid penetrant techniques.

The first side frame tested contained indications in the spring seat radius and the pedestal radius. This side frame showed only small changes in the defect sizes throughout the duration of the test. Defects in the spring seat radius ranged in growth from 0.15 inch to 0.4 inch. Growth in the pedestal radius ranged from 0.23 inch to 0.38 inch. The second and third side frames tested both had smaller initial indications when compared to the first side frame. As a result, no changes were observed for the indications in side frame two or three.

The initial indication located in the brake rode hole of the bolster grew throughout testing and eventually led to the failure of the part. Catastrophic failure occurred during the bounce load cycle after approximately 450,000 total cycles.

Figure 6 displays the fracture face of the bolster after failure. Initial inspection of the fracture surface shows that the fatigue fracture had multiple adjacent parallel crack origins as indicated by the presence of several ratchet marks on the final fracture surface. These cracks were oriented parallel to grind marks on the bolster surface, which may have acted as the fatigue initiation sites.

The fatigue crack propagated through the lower portion of the bolster and intersected with two casting inclusions before experiencing final cleavage fracture. TTCI continues to investigate the cause of this failure.

Figure 6. Fracture Surface of Failed Bolster

FUTURE WORK

TTCI will continue to develop and refine the FEA models described in this TD. Additional reports will describe in detail the results of the FEA for bolsters and side frames with and without defects. A nonlinear approach will be used to evaluate the influence of stress risers and casting defects in bolsters and side frames. Fatigue analyses of both components, with and without defects, will be completed under various material conditions. TTCI plans to conduct small-scale fatigue tests on bolsters and side frames to generate more accurate stress and strain life curves for the material.

At the conclusion of all of the FEA and fatigue analyses, TTCI will produce recommended guidelines for allowable defect sizes in bolsters and side frames. These guidelines will be provided to the AAR Coupling Systems and Truck Castings Committee for consideration. In addition to the guidelines, TTCI will aid in the refinement of nondestructive inspection techniques in the critical areas identified by the analyses.

ACKNOWLEDGEMENT

TTCI thanks ESI for its expertise in development and refinement of the FEA models used in this analysis.

REFERENCES

1. Morella, N., J. Wallace, and R. Maino. February 1978. "Study of the Fatigue Life Characteristics of Cast Steel Used in the Railroad Industry," Research Report R-299, Association of American Railroads.
2. Association of American Railroads. 2005. *Manual of Standards and Recommended Practices*, Section S, "Casting Details," Specification M-202 and Specification M-203, Washington, D.C.