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FEA Stress Determination for Weld Fatigue Using Hot-Spot Stress Method: Benchmarking and Rail Application

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ABSTRACT

Welded joints in rail steel structures are typically assessed for fatigue using two different stress range approaches: nominal stress range and hot-spot stress range when using SN methods. The nominal stress range is a traditionally simplified method that provides a conservative estimation but lacks accuracy in considering stress concentrations. On the other hand, the hot-spot stress range method is a more advanced and refined approach that offers a more precise evaluation of stress concentration, making it suitable for complex geometries. The BS7608-2015 British standard, Guide to Fatigue Design and Assessment of Steel Products, incorporated the hot-spot method for evaluating weld joints, especially when using numerical methods such as Finite Element Analysis (FEA). The weld classes are now categorically defined for both nominal and hot-spot approaches in new introductions, whereas earlier, it was based on the nominal stress approach only. Choosing the appropriate stress method depends on various factors, including the weld joint geometry, stress orientations, loading conditions, the desired level of accuracy, and primarily the available SN curve data for predicting fatigue damage. The work presented in this paper explores the hot-spot stress approach for determining stress in weld fatigue assessment for Rail Track Maintenance Equipment. The identified welds were assessed for variation in hot-spot stress on different mesh types, weld modeling techniques, and their effect on the fatigue damage factor using IIW and BS7608 guidelines. The joints under study were F2 and D class with nominal and hot-spot stress assessment, respectively, as per BS7608. These are more common weld joints in structural evaluations of rail equipment. The hot-spot approach for stress variation was studied on smaller models first. Subsequently, the approach was applied to assess the weld fatigue in rail equipment, and the results were compared with those obtained using the nominal stress approach.

1. INTRODUCTION

Ensuring the structural integrity and durability of rail welded equipment is critical for the safety of both the rail infrastructure and the equipment itself. The prediction of weld fatigue life using the stress-life (S-N) method is one of the most widely used approach in ensuring the structural durability of rail equipment. The main controlling parameter in S-N based fatigue life prediction is the stress range cycles that the equipment and welds will see during the use. The weld toe is one of the primary sources of fatigue cracking due to the severity of the stress concentration it generates [1-4]. Several geometric features in welded parts act as a stress raiser. Such stress raising discontinuities can produce essentially global and local effects producing high local stresses at welds. The stress concentration effect at welded joints, resulting from geometric changes, misalignments, material inconsistencies, and defects from the welding process, makes welded connections more susceptible to early failure compared to base materials. There are four primary methods to estimate the fatigue life of welded components: 1) The nominal stress method; 2) The hot-spot stress or strain method; 3) The local notch stress or strain method; and 4) The fracture mechanics method. These methods differ in the stress and strain levels they use, depending on how stress concentrators are accounted for in the calculations. Incorporating the Finite Element Analysis (FEA) method into the fatigue design of steel structures has facilitated the creation of localized stress analysis techniques. These include the Hot-Spot Stress (HSS) method, the notch stress method, and crack growth analysis [5]. In rail steel structures, welded joints are typically evaluated for fatigue using the nominal stress and HSS approaches when using S-N methods. The selection of the appropriate stress range method depends on several factors, including the geometry of the weld joint, stress orientations, loading conditions, desired accuracy level, and primarily the availability of relevant S-N curve data for predicting fatigue damage. The nominal stress range method is traditionally simplified approach, it tends to provide a conservative estimate, it lacks precision in accounting for stress concentrations. Conversely, the HSS method is a more advanced and refined approach that offers a more detailed evaluation of stress concentration, making it suitable for complex geometries [1-3, 5-9]. The nominal stress at a specific location is the combined total of membrane stress and bending stress at that point. Nominal stress is typically calculated using analytically derived formulas from theory. It excludes the effects of local structural discontinuities, stress concentration due to weld toe, thickness changes, residual stresses, and misalignments. A hot-spot in a structure is a location where a fatigue crack is likely to begin, resulting from the combined effects of fluctuating stress, geometric discontinuities, and weld geometry. The HSS approach evaluates stress near the weld; the hot-spot stress (HSS) is the structural stress at the weld toe or weld end. It includes the stress concentration effects of gross structural discontinuities, misalignment, and weld geometry but excludes the nonlinear peak stress caused by the local notch at the weld toe, although the HSS is positioned at the weld toe [2, 3]. Figure 1 shows the variation in structural stress approaching the weld toe.

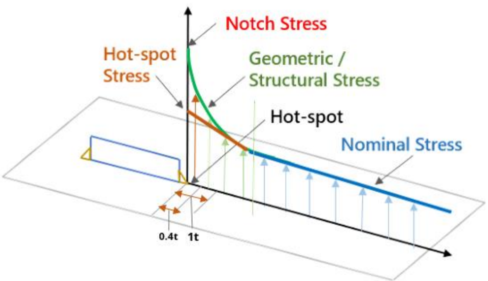


Figure 1. Structural stress

A local notch does not alter the membrane and shell bending structural stress. The primary effect of a notch is the local nonlinear peak stress distribution. This nonlinear peak lies within a radius of approximately 0.3t-0.4t from the notch root [2, 3, 5-8, 10]. Although the weld profile requirements are specified, the exact weld geometry and the shape of the local notch at the weld toe varies considerably along the weld and among different welds. As a result, the nonlinear stress peak at weld toe due to local notch exhibit unpredictable values. The nominal stress approach and HSS approach both include the random high stress caused by notches in the test results, which appears as a spread in fatigue S-N curves. As a result, calculating nonlinear stress peaks is not required; instead, they should be excluded from the calculated or measured nominal or hot-spot stress when applying these two methods in fatigue assessments [2, 3, 5-8]. The HSS method is applicable to welded joints under the following conditions [2, 3]:

1. The fatigue stress predominantly acts perpendicular to the weld or at the ends of weld.
2. The method is limited to potential fatigue crack initiation at the weld toe or end on the surface.

The hot-spot stress method does not apply to fatigue cracks that start and propagate from the weld root. It requires separate fatigue assessment using nominal stress or other approaches, is not part of this study. The HSS method is intended for assessing fatigue at the weld toe, where external geometric stress concentrations dominate. The HSS method primarily addresses stress concentrations at the weld toe, where geometric factors elevate stress levels. For fatigue cracks initiating from the weld root, alternative methods that address the unique stress distribution and initiation mechanisms at the root are required. Fatigue cracks originating from the weld root exhibit a different stress distribution that is less affected by external geometry, HSS method does not accommodate these specific stress characteristics at the weld root. The weld root's internal position complicates accurate stress measurement using surface-based methods like HSS. Fatigue cracks at the weld root often initiate due to factors such as lack of penetration, inclusions, or root defects, which differ from the geometric stress concentration effects at the weld toe. The HSS method does not consider these specific initiation mechanisms. Therefore, assumptions and calculations from the HSS method are applied only to potential crack initiation at the weld toe.

Figure 2 shows the two types of hot-spot in a structure. Type 'a' is located at the weld toe on a plate surface, and Type 'b' is located at weld toe on a plate edge [2, 3]. The HSS cannot be directly probed or measured from FEA or experimental results. It is determined using linear Surface Stress Extrapolation (SSE) with two reference points for type 'a' hot-spot and quadratic surface stress extrapolation with three reference points for type 'b' hot-spot [1-3]. The Type 'a' hot-spot is more commonly observed in welded structure, for which the SSE method involves linear extrapolation from stresses on the surface at distances of 0.4t and 1.0t from the weld toe. The corresponding hot-spot structural stress is given by Eq. (1) [1-3]. In type 'a' hot-spot, the stress distribution approaching the weld toe is a function of plate thickness, whereas it is not in type 'b' hot-spot [1-3]. Extrapolation methods for type 'b' hot-spot use stresses located at absolute distances from the weld toe rather than proportions of plate thickness, as given in Eq. (2). There is detail guidance given in IIW and BS7608 documents on stress extrapolation based on joint type, hot-spot type, and mesh size. This study is based on relatively finer mesh for type 'a' hot-spot that uses Eq. (1) suggested in IIW and BS7608 guidelines [1-4].

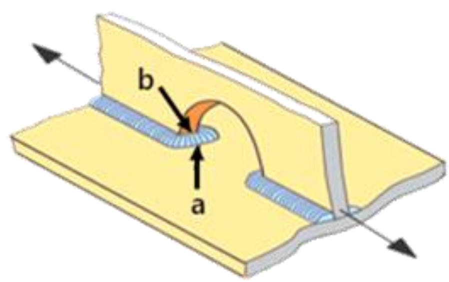


Figure 2. Type of hot-spots [2-4]

$$\sigma_{HS} = 1.67\sigma_{0\cdot 4t} - 0.67\sigma_{1\cdot 0t} \quad (1)$$

$$\sigma_{HS} = 3\sigma_{4mm} - 3\sigma_{8mm} + \sigma_{12mm} \quad (2)$$

The early design guideline for incorporating structural stress was outlined in Eurocode-3 ENV 1993-1 [11]. Subsequently, the International Institute of Welding (IIW) developed the extensive guidelines and recommendations for applying structural hot-spot stress, detailing elements such as type, size, and reference points [2-4]. While the HSS method has long been used for fatigue assessment of tubular structures, its application to plate structures is relatively recent. The HSS method has recently been incorporated into standards BS7608-2015, the Guide to Fatigue Design and Assessment of Steel Products [1]. The use of FEA for determining design stresses in fatigue life calculations has largely been increasing, driven by advancements in numerical applications. This trend is particularly notable for local approaches such as notch stress, fracture mechanics, and hot-spot stress methods. In fact, FEA has facilitated the development of local fatigue assessment methods, such as the Notch Stress and Hot-spot Stress approaches. The main disadvantage of the HSS method is its sensitivity to mesh type, element size, weld modeling techniques and accuracy in probing readings on reference points on the Finite Element (FE) model [5-9, 12, 13]. Even when well-built finite element models are used, FEA results can be highly sensitive to finite element modeling techniques, as the stress reference points for the HSS method are in areas of high stress gradients and stress singularities. As a result, the calculated stresses can vary based on element type, size, and weld modeling techniques in FEA, which can lead to over or under estimation of fatigue life.

The variation in hot-spot stress results primarily from how each element type represents and computes stress distribution under loading and geometric complexities, as well as the varied integration points used during calculations in the solution process. Shell elements are effective in capturing mid-surface stresses but may underestimate stress concentrations at sharp corners or complex weld geometries. Tetrahedral elements are popular and widely used for accurately capturing geometric features but provide less accurate results than hexahedral elements due to fewer integration points, which can lead to less accurate stress predictions, especially in regions with high stress gradients. Achieving accurate results with tetrahedral elements often requires a very fine mesh. If the mesh is not sufficiently refined, tetrahedral elements can produce higher stress values due to inadequate resolution of the stress field. Hexahedral elements are better suited for capturing localized stress variations. Modeling the weld surface explicitly allows the simulation to account for the additional stiffness and stress concentration effects caused by the weld geometry, providing a closer representation and more accurate results compared to simulations without weld surface modeling.

The primary goal of this work was to gain more clarity on applying the hot-spot stress method in assessing the weld fatigue in rail equipment, particularly focusing on how FEA stress determination and stress extraction for the HSS method works on FEA models with different mesh types and modeling techniques for welds. The identified welds were evaluated and compared for fatigue stress ranges using IIW and BS7608 guidelines for the hot-spot stress approach. The effect of various mesh types and finite element (FE) modeling on peak and structural stress was studied and presented. Subsequently, the hot-spot approach was applied to assess weld fatigue in rail equipment, and the results were compared with those obtained using the nominal stress approach. The study examined the lap joint and T-joint fillet welds, categorized as F2 with the nominal stress approach and as category D with the hot-spot stress approach according to BS-7608 guidelines. Appropriate fatigue strength S-N curves for welds in class D and F2 were used from BS7608 in fatigue damage factor calculation. The fatigue requirements for track-induced loads on rail equipment are described in various regulatory codes [1, 11, 14-18]. The regulations to apply vary depending on where the equipment will be operated and the specific requirements of the machine. This study aims to compare stress ranges by utilizing benchmark models subjected to consistent loads for deriving weld stress. It employs various mesh types and FE modeling techniques to assess hot-spot stress. The track induced vertical travel fatigue load applied to the rail vehicle model was referenced from EN12663 [15]. Additionally, BS7608 [1] was used to determine weld joint classifications and to derive fatigue estimates from the S-N curves for both nominal and hot-spot stress methods.

2. PROCESS, SIMULATION MODELS

Figure 3 illustrates the typical steps involved in weld fatigue assessment for rail track maintenance equipment. The initial step involves establishing design life criteria, which are determined by the product's applications, intended use, requirements, and regulatory standards. In this evaluation, the comparative study conducted on welds in geometric models shown in Figure 4 doesn't necessitate fatigue criteria. Instead, the focus lies on comparing fatigue stress range results and structural stress using the hot-spot method across different mesh and modeling techniques. Figure 5 shows the rail equipment model, where the HSS method was utilized to evaluate critical welds with different mesh types, comparing stress and fatigue damage factors over a desired 4 million load cycles based on its intended usage in travel configuration [14].

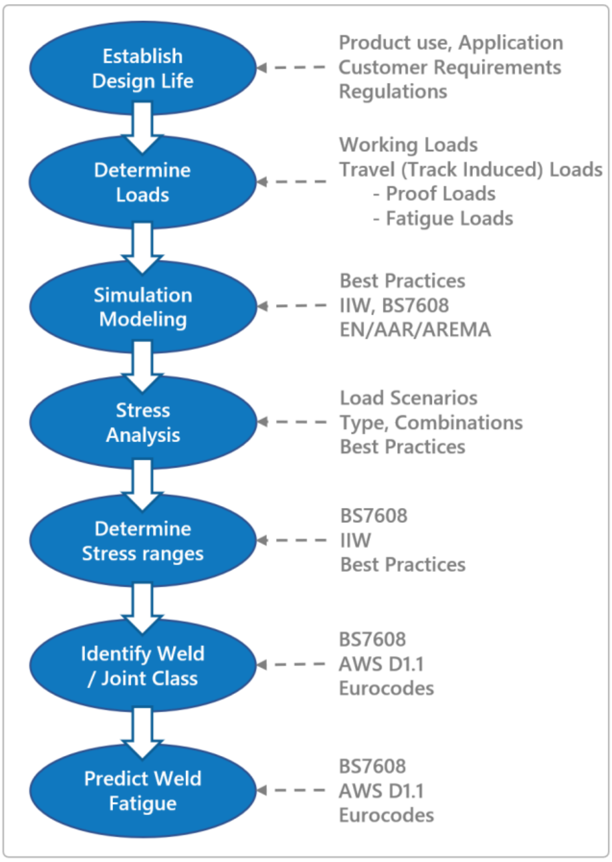


Figure 3. Steps in weld fatigue assessment

In the second step, equipment working, and travel loads are determined. Working loads are typically established by the manufacturer based on the machine's capacity and intended use, while track-induced travel loads are generally recommended in regulatory guidelines for an infinite life approach. Alternatively, some regulations suggest alternate loads for the cumulative damage method, allowing manufacturers to instrument their own equipment and provide realistic data for specific applications. The rail equipment model shown in Figure 5 was analyzed under a 1±0.3g vertical load, referenced from EN-12663 and EN-14033, is a typical vertical track-induced travel fatigue load for infinite life approach. Although the load is standard, its use in the presented study is for comparative purposes to observe the variation in HSS due to different mesh types, weld modeling techniques and their effect on the fatigue damage factor. The regulatory guidelines and industry best practices are then used to build FEA/Simulation models, based on the analysis objective, analysis type, and the specific weld and fatigue assessment needed. The work presented here is divided into two main parts:

1. Hot-spot stress range and structural stress study on simplified models shown in Figure 4.
2. HSS method application to rail equipment for stress range and fatigue damage comparison on different mesh types, and with nominal stress.

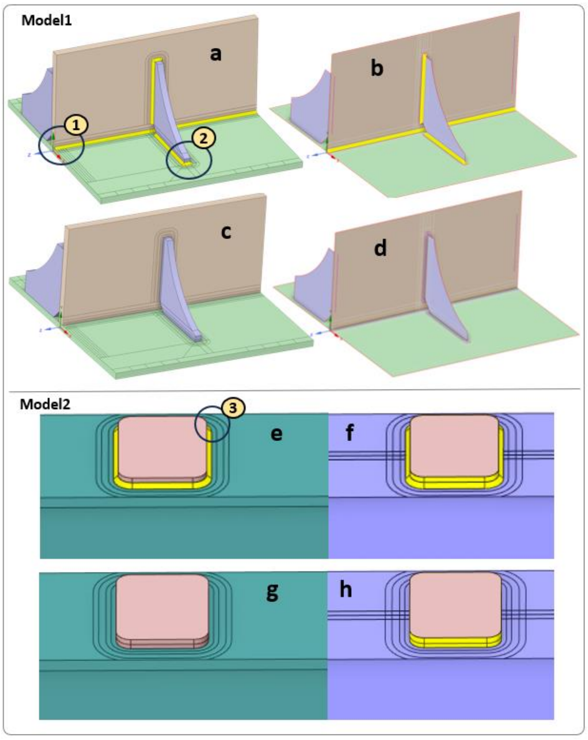


Figure 4. Geometry models for FEA HSS study

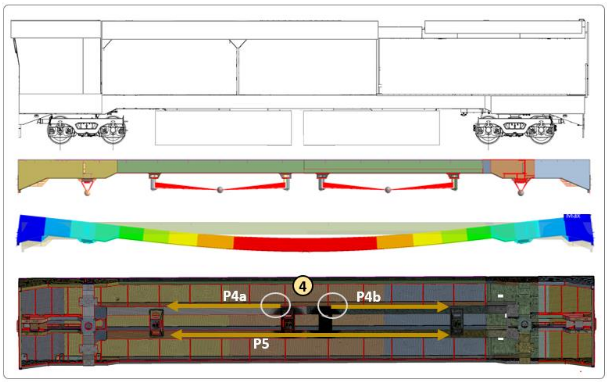


Figure 5. Rail vehicle model for HSS fatigue study

The geometry models shown in Figure 4 are classified into two main groups: one with weld surface modeling and the other without. Each group model was studied for solid tetrahedral, hexahedral dominant, and shell mesh, with both linear and 2nd order elements for each type for comparative study. The rail equipment model shown in Figure 5 was analyzed using higher-order solid and shell element types to compare hot-spot stress and fatigue damage factor across different mesh types, as well as with nominal stress. Mesh size was kept consistent across all models, with an overall fine mesh having element sizes of 0.15-0.3 inches, ensuring that at least one or more nodes lie within a distance of 0.4t thickness from the weld toe. The sphere of influence and local sizing options were utilized to achieve a fine mesh in identified hot-spot areas. Welds were created using bonded contact definitions with default formulations in solid element and using shared topology on mid-surface models.

In the subsequent step, simulations are performed for the required loads and machine configurations, whether for working conditions or travel, to determine stress levels for further assessment based on the load and joint types. In this study, FEA benchmark models were solved using various mesh types and FE weld modeling scenarios in Ansys Mechanical software. The rail vehicle model analyzed for the vertical track-induced load, as specified earlier. Ansys Mechanical software was used for the analysis and extraction of stress results at reference points and selected paths in the areas of interest. Nominal stress was derived through analytical calculations and curve fitting applied to the stress data extracted from the FEA solution. The solution combination feature was used to obtain stress ranges in the rail vehicle model. Once stress ranges are probed and/or calculated using the nominal and hot-spot methods, the next step is to determine the weld joint class. Regulatory codes provide several tables that can be used to determine the weld class for further fatigue calculations. It is important that the class used, and fatigue strength S-N curve data remain consistent in the calculations. In the current analysis, particularly in the rail vehicle model where further fatigue damage calculation was conducted, the weld joint class for identified critical welds was determined from BS7608. Fatigue strength S-N curves corresponding to each determined class were referenced from BS7608 for predicting fatigue damage.

3. RESULTS

3.1 Results: model 1 and model 2

The benchmark models were solved with and without weld surface modeling, utilizing tetrahedral solid mesh, hexahedral dominant solid mesh, and shell mesh on midsurfaces, incorporating both 1st and 2nd-order elements for each element type. Due to the length of the document, all stress plots and graphs for each version are not included here; however, all results are summarized in Tables 1-8. Some stress plots are displayed in Figure 6 for model 1 versions with T-joint fillet welds and in Figure 7 for model 2 versions with lap joint fillet welds. Three hot spots were identified, as shown in Figures 6 and 7, for the HSS study. The stress readings were probed at 0.4t and 1.0t thickness distance away for each solved model. Split lines were created at and next to welds on the geometry surfaces to precisely probe stress readings at distances of 0.4t and 1.0t. An alternative method is to extract stress along paths created at the identified critical welds in the direction perpendicular to stress, which was also done to study the stress variation approaching the weld toe for comparison. The hot-spot stress is calculated from the probed values at reference points using BS7608 and IIW guidelines, with Eq. (1) discussed in the introduction section. The hex dominant mesh indicated consistent results across all models, falling somewhere between the results obtained with tetrahedral and shell elements. The ratios are calculated in each table to indicate the relative difference between results, with a reference value of hex dominant mesh of higher order in each respective table.

The results in Tables 1-3 and the bar charts in Figures 8-10 correspond to spot 1 in model 1, whereas the results in Tables

4-6 and the bar charts in Figures 11-13 correspond to spot 2 in model 1. The results in Table 7 and Figure 14 correspond to spot 3 in model 2. Table 1 compares the HSS within different element types and their order, maintaining consistent weld surface modeling across all models in this table. Each table presents two comparisons: one within the same element type regarding element order, and the other across different element types. The results indicate that the shell element modeling predicts higher HSS values compared to both hexahedral and tetrahedral element modeling. It is well known that linear order tetrahedral elements do not produce accurate results; they significantly underestimate the results. However, both hexahedral and shell mesh models predict very close results regardless of their element order. Across all three element types with higher order, the predicted HSS values shows the variations up to 4% within each group. Table 2 lists similar results as in Table 1 without weld surface modeling in FE model weld connections. It indicates comparable findings within group results, with predicted HSS values showing variations up to 7% within each group. Additional findings from the inter-group comparison between Tables 1 and 2, for models with and without weld surface modeling, are separately presented in Table 3. It is observed that without weld surface modeling, higher HSS values are predicted in each element type. Within element types with weld surface modeling, there is less variation; the results show variations within 4%, compared to 7% variations in models without weld surface. Based on the outcomes of the first set of results, model 2 was examined with higher-order elements both with and without weld surface modeling for lap joint fillet weld. The findings from model 2 are similar to model 1, except for one variation: where the shell models predicted lower HSS values than other elements, the tetrahedral elements predicted the highest values in the group. The percentage variation within the group is within 4%.

The stress extracted at weld toes for the identified welds shown in Figures 15 and 16 for spot 1 and 2 respectively. The elements with linear order, especially the tetrahedral, exhibit an erratic stress pattern approaching the weld toe from the toe to 0.4t distance. The peak stress value and stress variation are significant from model to model and within each element type; however, the stress values and trends are very similar after 0.4t distance in all models. The graphs shown are not to scale; they are presented to observe stress variation behavior approaching the weld toe within 0.4t and 1.0t thickness distance away. The models with shell mesh show a significant drop in stress at and right next to the weld toe intersection modeling which improves when weld surfaces are modeled and with a finer mesh. In FEA of welded structures using shell elements, it is common to observe a drop in stress at and near the weld toe intersection. Shell elements are typically used to model the mid-surface of the structure. When welds are not explicitly modeled, the weld geometry is simplified, which can lead to inaccuracies in stress distribution, particularly at stress concentration points like the weld toe. This can be improved by refining the mesh and modeling the weld surfaces. The finer mesh enhances resolution and captures stress gradients more effectively due to a greater number of nodes and elements, while the weld modeling accounts for the additional stiffness of weld geometry, accurately capturing stress concentration effects. The results showed that this inaccuracy is within a 0.4t thickness distance for the relatively finer mesh size used. The calculated HSS is not significantly affected by this inaccuracy, as the first readings were probed at a 0.4t distance.

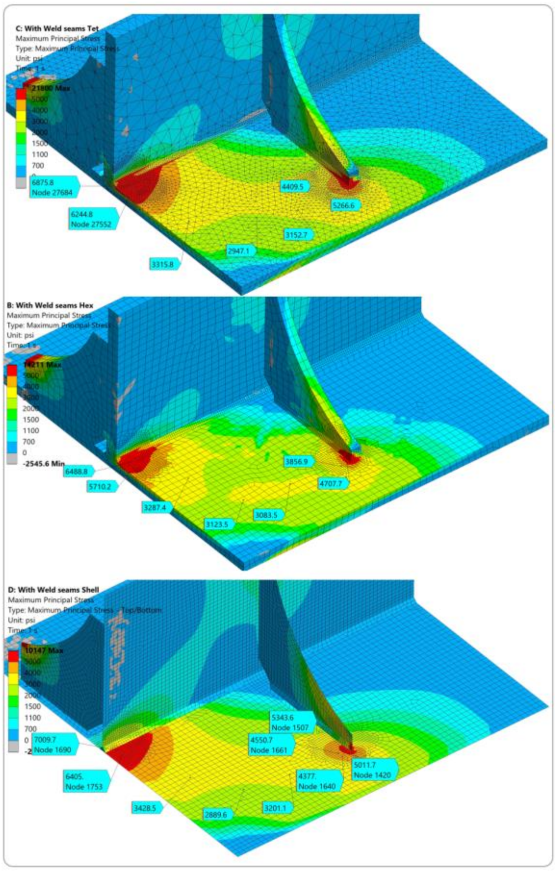


Figure 6. Model 1 stress plots on various mesh types

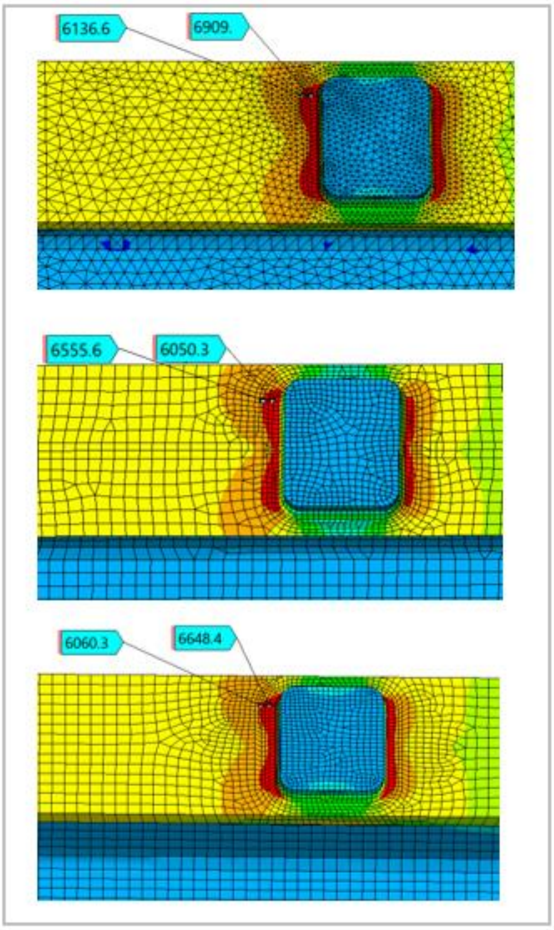


Figure 7. Model 2 stress plots on various mesh types

Table 1. HSS with weld surface modeling at model 1-spot 1

SN	Mesh Type	Order	Principal Stress in PSI			
			0.4t	1t	HSS	Ratio
1	Solid Tetra	1	5028	4152	5615	0.782
2	Solid Hex	1	6488	5710	7009	0.976
3	Shell	1	7010	6405	7415	1.032
4	Solid Tetra	2	6875	6244	7298	1.016
5	Solid Hex	2	6813	6261	7183	1.000
6	Shell	2	7014	6413	7417	1.033

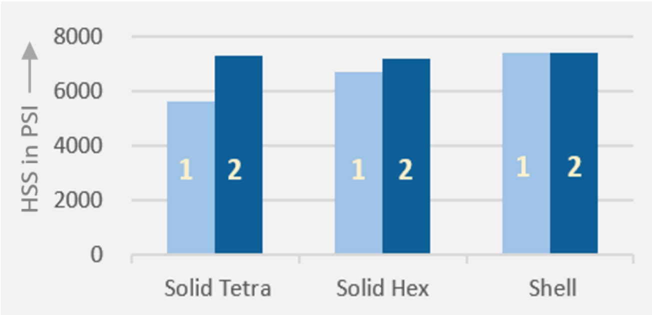


Figure 8. HSS bar charts of Table 1 data

Table 2. HSS without weld surface modeling at model 1-spot 1

SN	Mesh Type	Order	Principal Stress in PSI			
			0.4t	1t	HSS	Ratio
1	Solid Tetra	1	5077	4479	5478	0.744
2	Solid Hex	1	6898	6070	7453	1.013
3	Shell	1	7432	6784	7866	1.069
4	Solid Tetra	2	7027	6329	7495	1.018
5	Solid Hex	2	6955	6352	7359	1.000
6	Shell	2	7435	6790	7867	1.069

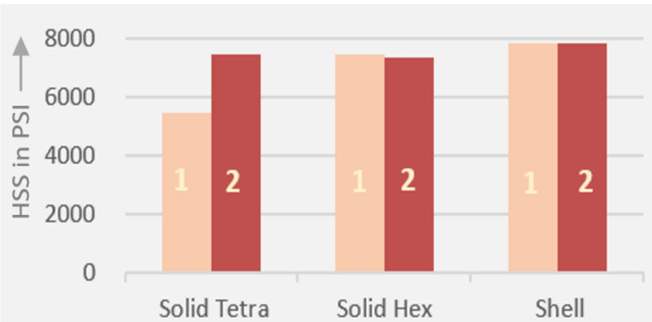


Figure 9. HSS bar charts of Table 2 data

Table 3. HSS with and without weld surface at model 1-spot 1

SN	Mesh Type	Weld	Principal Stress in PSI			
			0.4t	1t	HSS	Ratio
1	Solid Tetra	No	7027	6329	7495	1.043
2	Solid Hex	No	6955	6352	7359	1.025
3	Shell	No	7435	6790	7867	1.095
4	Solid Tetra	Yes	6875	6244	7298	1.016
5	Solid Hex	Yes	6813	6261	7183	1.000
6	Shell	Yes	7014	6413	7417	1.033

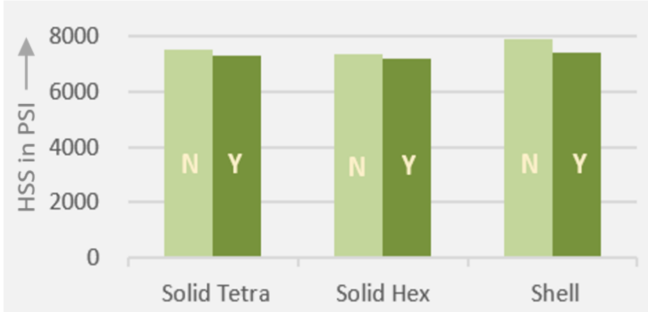


Figure 10. HSS bar charts of Table 3 data

Table 4. HSS with weld surface modeling at model 1-spot 2

SN	Mesh Type	Order	Principal Stress in PSI			
			0.4t	1t	HSS	Ratio
1	Solid Tetra	1	3799	2924	4385	0.743
2	Solid Hex	1	4670	3819	5240	0.888
3	Shell	1	5343	4550	5874	0.995
4	Solid Tetra	2	5266	4409	5840	0.989
5	Solid Hex	2	5306	4414	5904	1.000
6	Shell	2	5360	4569	5890	0.998

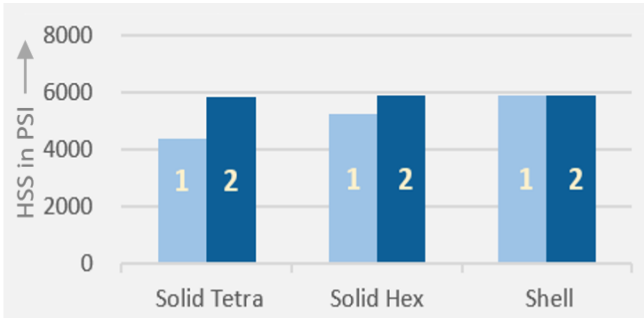


Figure 11. HSS bar charts of Table 4 data

Table 5. HSS without weld surface modeling at model 1-spot 2

SN	Mesh Type	Order	Principal Stress in PSI			
			0.4t	1t	HSS	Ratio
1	Solid Tetra	1	4308	3371	4936	0.812
2	Solid Hex	1	5503	4413	6233	1.025
3	Shell	1	5986	4887	6722	1.106
4	Solid Tetra	2	5484	4579	6090	1.002
5	Solid Hex	2	5487	4601	6081	1.000
6	Shell	2	6030	4879	6801	1.118

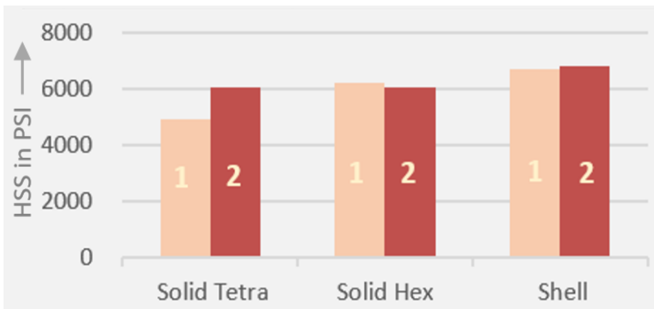


Figure 12. HSS bar charts of Table 5 data

Table 6. HSS with and without weld surface at model 1-spot 2

SN	Mesh Type	Weld	Principal Stress in PSI			
			0.4t	1t	HSS	Ratio
1	Solid Tetra	No	5484	4579	6090	1.032
2	Solid Hex	No	5487	4601	6081	1.030
3	Shell	No	6030	4879	6801	1.152
4	Solid Tetra	Yes	5266	4409	5840	0.989
5	Solid Hex	Yes	5306	4414	5904	1.000
6	Shell	Yes	5360	4569	5890	0.998

Table 7. HSS with and without weld surface at model 2-spot 3

SN	Mesh Type	Order	Principal Stress in PSI			
			0.4t	1t	HSS	Ratio
1	Solid Tetra	1	6825	6077	7326	1.040
2	Solid Hex	1	6751	6172	7139	1.014
3	Shell	1	6708	6127	7097	1.008
4	Solid Tetra	2	6909	6136	7427	1.055
5	Solid Hex	2	6648	6060	7042	1.000
6	Shell	2	6555	6050	6893	0.979

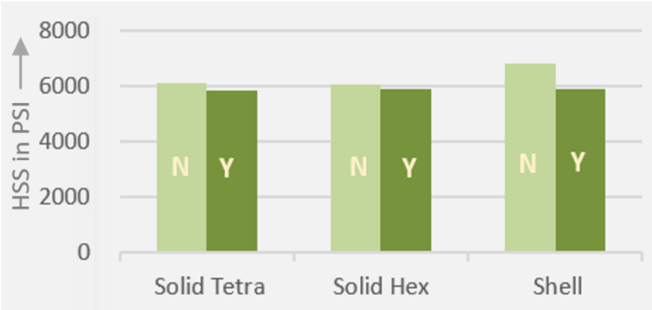


Figure 13. HSS bar charts of Table 6 data

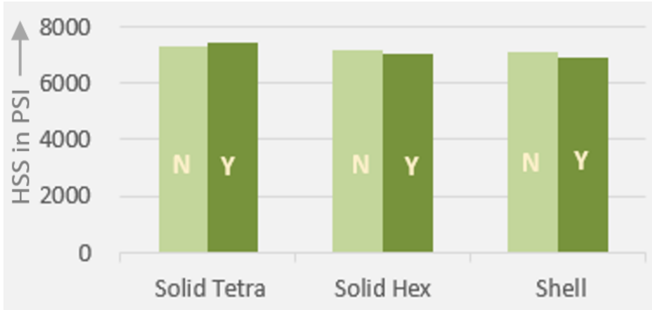


Figure 14. HSS bar charts of Table 7 data

Table 8. Hot-spot stress, nominal stress and fatigue damage factor compared on rail vehicle model

Stress Type and Weld Location Description	Weld Class	Load	Mesh Type	Principal Stress Range PSI		Stress Range	Stress Ratio	Damage Factor
				0.4t	1t			
HS stress at weld toe - spot4a	D	±0.3g Vertical	Solid Tetra	9974	7838	11405	1.041	1.31
			Solid Hex	9688	7789	10960	1.000	1.16
			Shell	9634	7913	10787	0.984	1.11
HS stress at end of weld - spot4b	D	±0.3g Vertical	Solid Tetra	9256	7848	10199	1.067	0.94
			Solid Hex	8867	7832	9560	1.000	0.77
			Shell	8774	7637	9536	0.997	0.76
Nominal stress, FEA	F2	±0.3g Vertical	NA	NA	NA	7168	NA	1.14
Nominal stress, analytical			NA	NA	NA	7644	NA	1.39

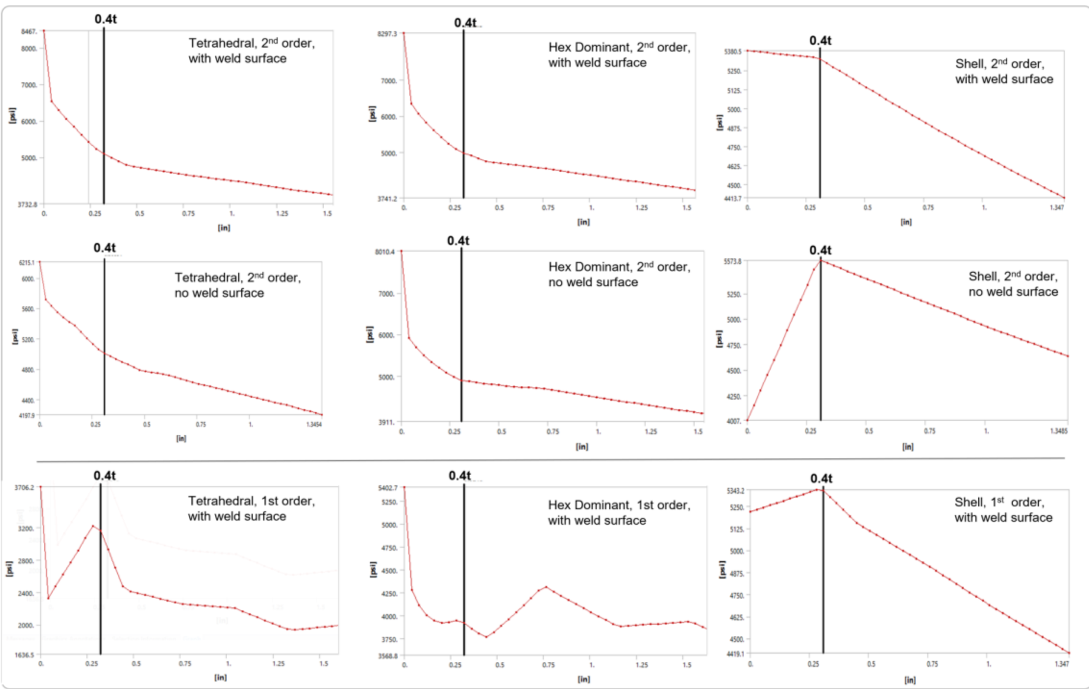


Figure 15. FEA stress extracted at weld toe on various mesh types and weld surface modelling in model 1 at spot 1

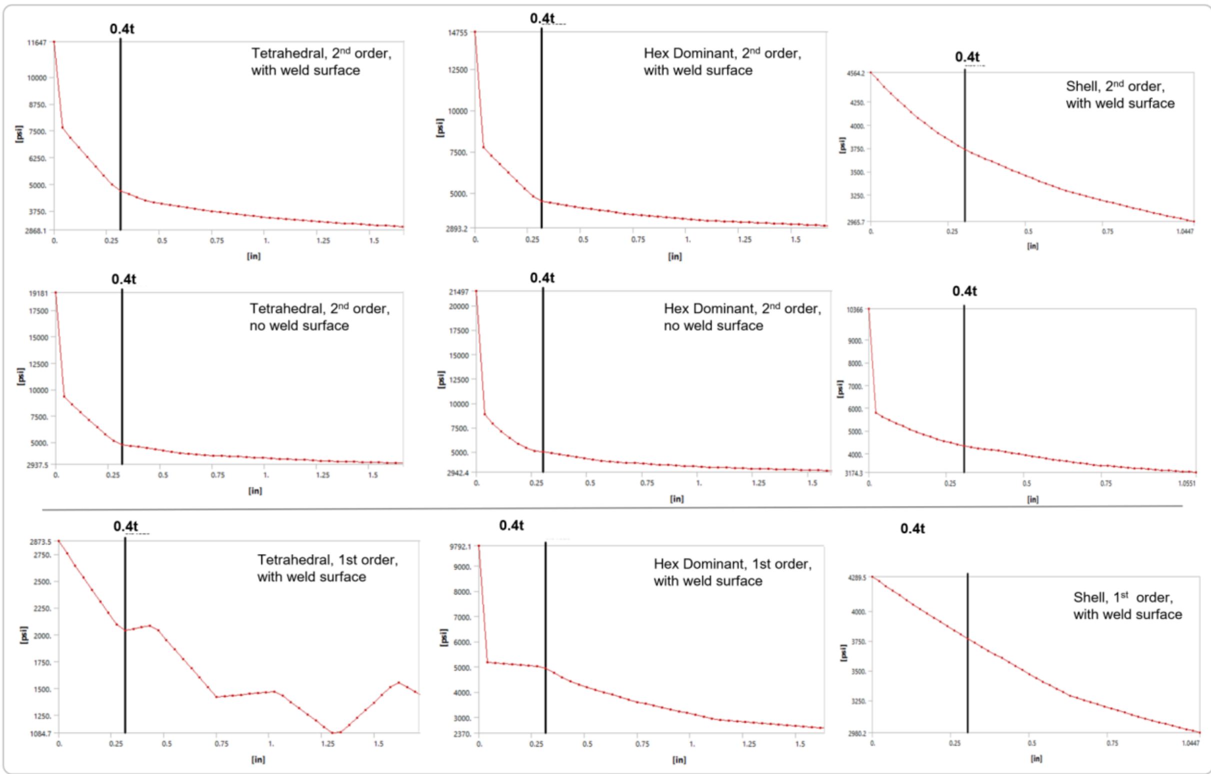


Figure 16. FEA stress extracted at weld toe on various mesh types and weld surface modeling in model 1 at spot 2

3.2 Results: Rail equipment model

The results shown in Figures 17 and 18 are the nominal and hotspot stress results on the rail vehicle model. Figure 17 illustrates both the analytical and FEA extracted stress data before and after adding welds to critical areas of the I-beam. Figure 18 presents an image of the analytical calculations performed to obtain the nominal stress. The identified welds were evaluated for nominal stress using analytical methods as well as by curve fitting on extracted FEA stress data. The assessment of hot-spot stress was carried out using higher-order quad-dominant shell, tetrahedral, and hex-dominant element meshes, with the comparison of stress and fatigue damage factors detailed in Table 8. Figures 10, 11, and 12, in conjunction with Table 8, provide insights into two specific aspects: 1) The comparison of fatigue damage factors between Nominal and hot-spot stress, and 2) The variation in hot-spot stress ranges across different mesh types and its impact on fatigue damage factors. The equipment and other structural mass were distributed on the top decking plate of the frame, with an estimated total weight of around 160,000 lbs. The structural mass of the equipment mounted to the mainframe was accounted by creating point mass elements at respective CG points and attaching those to mounting areas on the mainframe. The miscellaneous mass was accounted by creating distributed mass across the mainframe. The geometry model was almost symmetric, with loads and boundary conditions applied symmetrically as well. The left side was created with a shell mesh on midsurfaces, while the right side was created with a solid mesh. The corresponding spots on the left and right are studied and compared for fatigue damage. The FE model was analyzed for 1g load, and the results were scaled down for fatigue load. Analytical calculations were also conducted for 1g load, and the nominal stress was scaled down for fatigue stress range. This evaluation is for HCF; the stress values are well within elastic limits, so scaling of stress for different load magnitudes is possible.

Overlaying the FEA and analytical stress data with potential weld classes on the graph enables the determination of whether a particular type of weld is suitable for the level of stress in that area. The analytically calculated nominal stress is higher than the FEA predicted nominal stress. Historically, Track Maintenance Equipment (TME) rail vehicle assessments show that most welds on the structure fall under class F2 joint classification with the nominal stress approach and class D with the hot-spot stress approach. The nominal stress results indicate that any possibility of an F2-type weld in the highlighted area within the rectangle on the I-beam shown in Figure 17 would likely not meet the fatigue requirements. However, the other overlaid results and further assessment of the hot-spot approach, as shown in Figure 19, indicate that there is a possibility of meeting the fatigue stress criteria if specific welds are assessed more closely using the hot-spot stress method. The six graphs in Figure 19 show extracted stress perpendicular to the weld at location 4, as identified in section 2. Location 4 was assessed for two welds: one at the weld toe and the other at the end of the weld. The extracted data is used for hot-spot stress range calculations using Eq. (1) given in the introduction section. The results are summarized in Table 8, which suggests the importance of the hot-spot stress method when the nominal approach tends to give conservative results. The use of the nominal theory remains a significant time saver, as its conservative results can be obtained very quickly to deem large portions of the structure safe, and then the hotspot method can be used to focus on areas of concern. The stress range obtained in tetrahedral elements is predicting slightly higher hot-spot stress range than on shell and hex-dominant solid mesh; however, the effect on fatigue factor is notable.

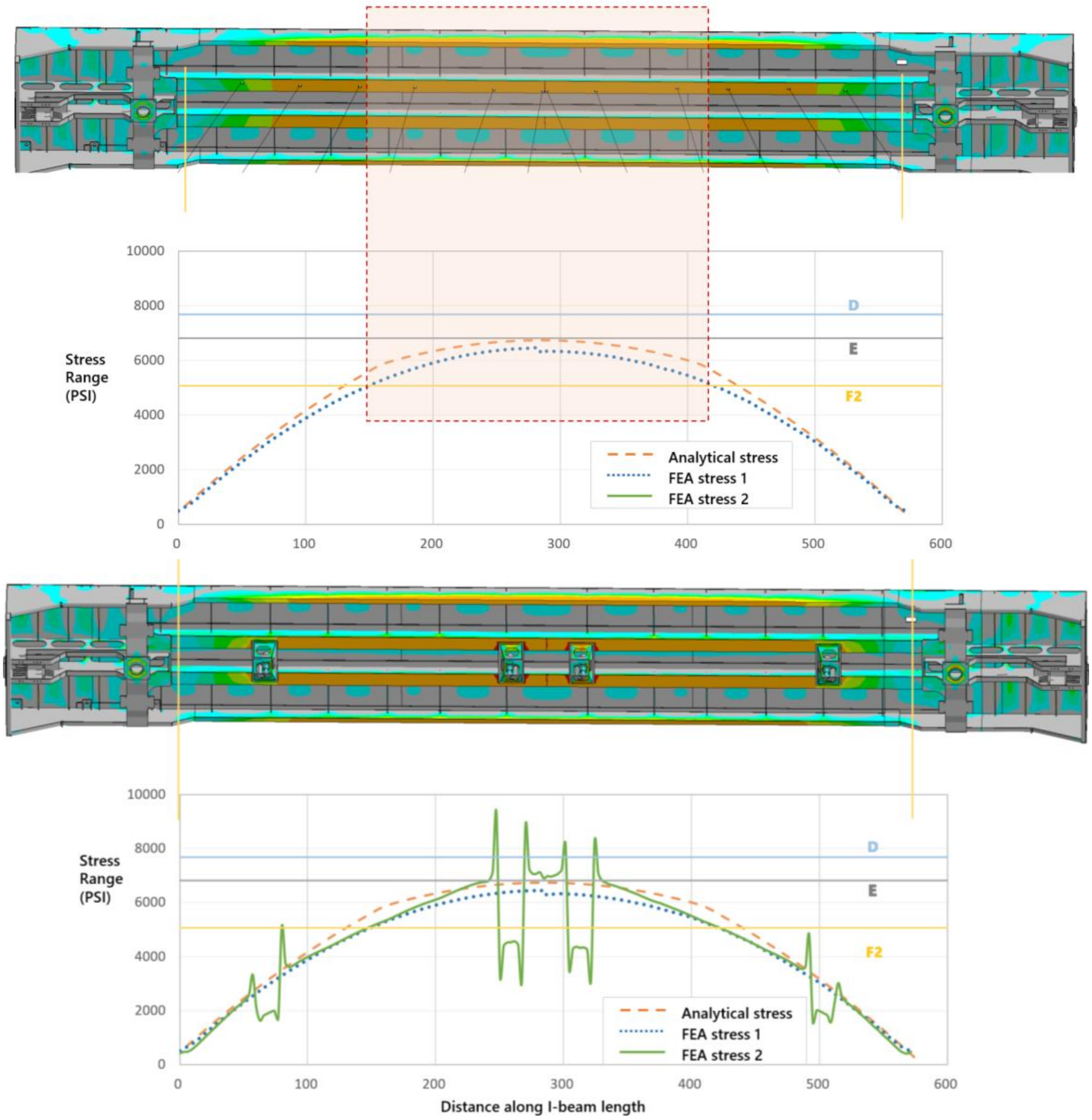
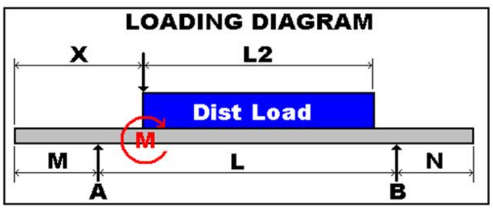


Figure 17. Nominal and hot-spot stress from analytical calculations and extracted FEA stress along I-beam



BEAM DIMENSIONS (inches):

M	L	N	TOTAL LENGTH	A
100	630	100	830	80,000

RESULTANT FORCES (lbs)

CONCENTRATED LOADS:

DESCRIPTION	lb LOAD F	DIST X
Carriage Front	12,000	291
Carriage Rear	12,000	539
Bogie Front	13,000	100
Bogie Rear	13,000	730

DISTRIBUTED LOADS:

DESCRIPTION	UNIT LOAD IN #/" LEFT	RIGHT	DIST DIST, X	LENGTH, L2	WEIGHT OF LOAD
DISTRIBUTED LOADS 1	120	120	65	700	84,000
DISTRIBUTED LOADS 2	200	200	0	65	13,000
DISTRIBUTED LOADS 3	200	200	765	65	13,000
	0	0	0	0	0

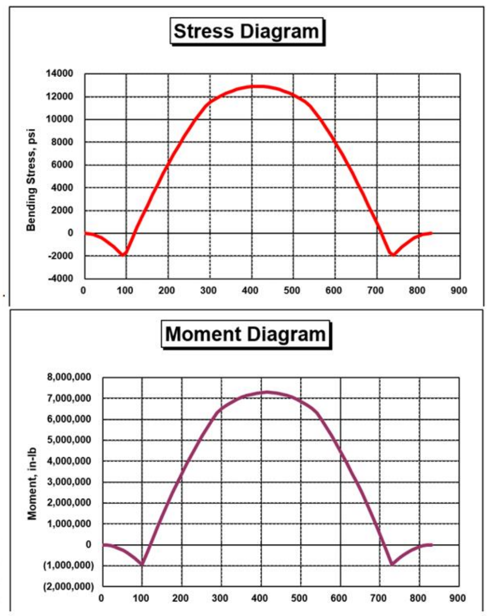


Figure 18. Analytical nominal stress calculations along the length of beam for 1g load

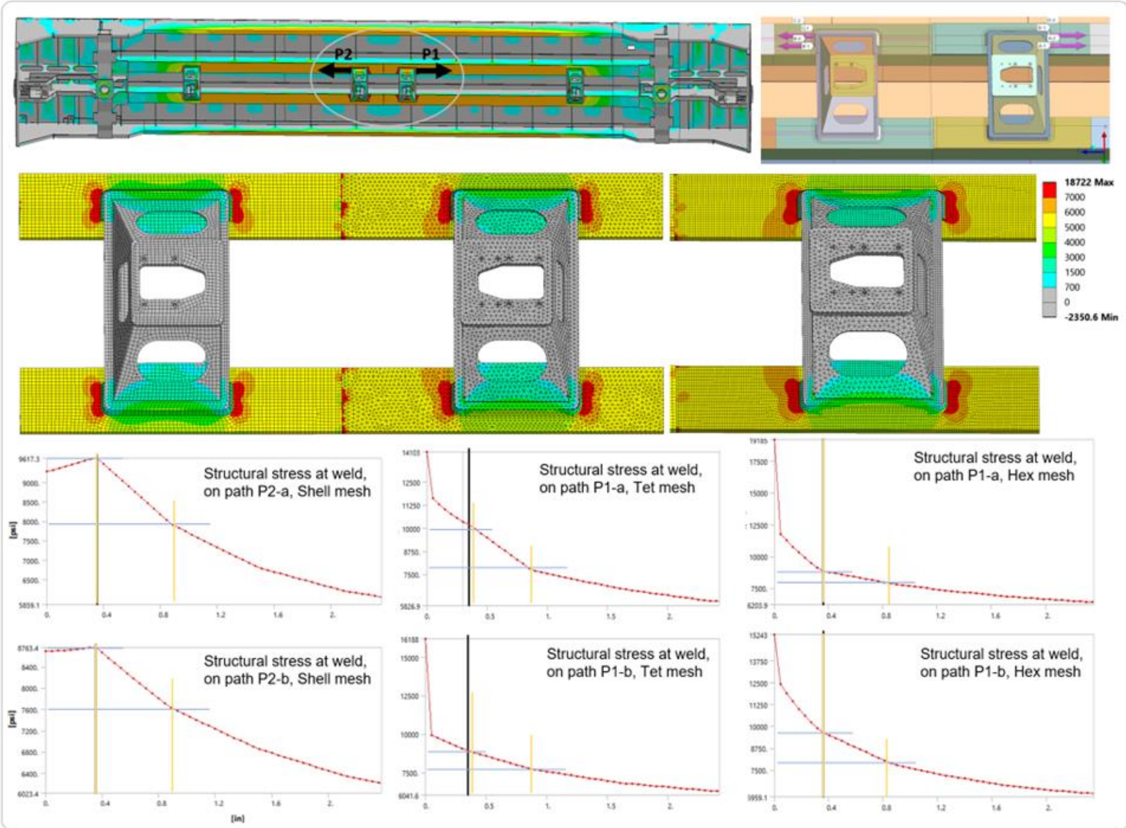


Figure 19. Stress extracted at welds for hot-spot stress and fatigue damage calculations

4. CONCLUSIONS

Hot-Spot Stress method can be used be used when joint classification is not defined for the nominal approach, and when joint complexity is higher and/or when it is not obvious to estimate the nominal stress in complex geometries; The study of TME mainframe critical welds with the nominal and hot-spot stress methods indicates the significance of the hot-spot stress method when the nominal approach tends to give conservative results. The use of the nominal theory remains a significant time saver, as its conservative results can be obtained very quickly to deem large portions of the structure safe, and then the hotspot method can be used to focus on the areas of concern. The hotspot approach works well for fatigue assessment of rail equipment, especially when the design fatigue loads, occurrences, criteria for determining stress ranges, and the relevant fatigue strength test data (S-N curves) to be used are generally defined in the regulatory codes and guidelines. The fatigue strength test data referring to various joints for nominal and hot-spot approach in BS7608; the HSS approach requires few S-N curves to evaluate more types of weld joints.

The peak stress value and structural stress variation are significant from model to model and within element types; however, the stress values and trends become similar after 0.4t distance in all models. Across all three element types with higher order, the predicted HSS values show variations up to 4% within each group; the shell elements predict very similar results regardless of the order. Within element types with weld surface modeling, there is less HSS variation; the results show variations within 4%, compared to 7% HSS variation in models without weld surfaces. The results on variations of benchmark model 1 for welds on t-joints indicates that the shell element modeling predicts higher HSS values compared to both hexahedral and tetrahedral element modeling, whereas the benchmark model 2 and full rail vehicle model indicated it opposite, the shell mesh on them underestimates the HSS at identified welds compare to solid mesh. The benchmark FEA/ simulation models with and without weld surfaces modeled, the findings indicate that the models without weld surfaces overpredict the hot-spot stress compared to those with weld surfaces. The values remain close and consistent within each group of higher order element types.

As pointed in other research, the results showed similar findings that the hot-spot stress method is sensitive to mesh element type, element size, and weld joint modeling. The HSS results and results relationship shown in this study varies from joint to joint and location to location within the structure. Although the deviation in stress ratio appears to be small, its impact on the fatigue damage factor could be significant. Some paths and locations in the FEA model showed inconsistent behavior, with very high stress in the notch and transition areas from the weld toe and away. The hot-spot stress is in areas of singularity and high stress gradients; high level of analyst skill is required in building accurate FE models, processing, and interpreting the result carefully for hot-spot method.

The comparative evaluation done in this study is limited to the specific joint geometry that fall under F2 class of weld in nominal stress method and for type-a hot-spot with class D in the HSS method. Although the study compares the relative variability of small data sets, the variations however studied on several such small datasets that provide good early insights into HSS variation and its impact on the fatigue damage factor in rail equipment. Further study is planned to gather more data for statistical significance, draw firm conclusions, conduct correlation work, study the effect of contact formulation on weld definitions available in modern FE software, and develop potential correction factors for models without weld surface modeling.

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