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GVSETS 2020 PAPER: FATIGUE-FOCUSED WELD ASSEMBLY OPTIMIZATION

Carly Mayhood[1], Nickolas Vlahopoulos, PhD[2]

[1] PhD Student, Naval Architecture and Marine Engineering, University of Michigan
[2] Professor, Graduate Program Chair, Naval Architecture and Marine Engineering, University of Michigan

ABSTRACT

This work presents the development and application of an optimization algorithm for simultaneously improving the fatigue life and minimizing a representative manufacturing cost when assembling a ground combat vehicle. High stress in the occupied space of the weld decreases the fatigue life of the structure; therefore, by minimizing the weld's exposure to high stresses, the structure's life can be improved. The new capability for simultaneously improving the fatigue life of a welded structure while reducing a manufacturing cost is demonstrated by considering the welding of a representative panel of a v-hull. Selections are made for the weld placement, the weld type, and the type of filler material, in order to minimize exposure to high stresses and therefore maximize fatigue life. In addition to the stress evaluation, the optimization considers manufacturing cost as another objective in parallel. The final evaluation provides an assembly design to increase the fatigue life and minimize cost.

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1. INTRODUCTION

The motivation for this work is to increase the readiness of US Army ground combat vehicles by increasing the fatigue life of the structure. While there are continuous improvements in defense and armor technologies to perform and survive the combat arena, these vehicles still have an underlying vulnerability in fatigue cracking of the welded joints that are necessary to assembling the structure from repeated, low level loading. This work sets out to minimize the risk of weld failure and therefore increase the availability of combat vehicle. This optimization considers changing the assembly of the structure in order to minimize the stress exposure of welds, reducing the risk of fatigue failure. This work considers how armor plate joints behave, then incorporates this information into design and assembly of these vehicles through a multi-disciplinary genetic algorithm.

2. MATERIAL BEHAVIOR

First, the behavior of materials specific to the combat vehicles needs to be understood in order to incorporate the information into the optimization. The armor grade materials exhibit unique high hardness and had to undergo systematic fatigue testing in order to ensure accurate estimation the fatigue life of these structures. Multiple combinations of base metals and filler material are in use on combat vehicles, so a representative selection of combinations were tested to fill out a welded joint S-N curve [1]. The mismatch ratio, defined as the yield strength of the consumable over the yield strength of the base metal, was used as the defining characteristic when deciding which joints to test. Three combinations were tested.

Base Metal	Consumable	Ratio
MIL-DTL-12560	E110C-G H4	0.665
MIL-DTL-46100	ER316LSi	0.283
MIL-DTL-12560	ER70S-6	0.415

These three combinations represent the highest, lowest, and mid-range mismatch ratios, providing a comprehensive understanding of behavior. Several quarter-inch welded joint strips of each variation were fatigue tested at load cases ranging from 16 to 20 kips, then the results were plotted onto a Master S-N curve of welded joints.

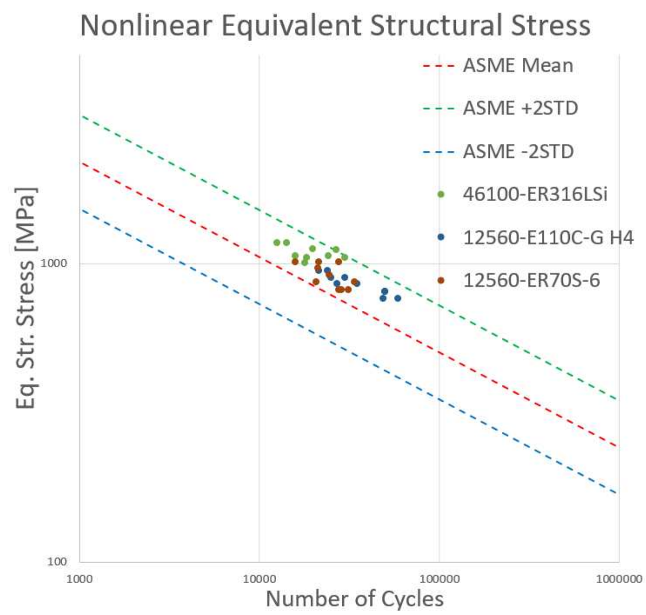

Figure 1. Master S-N plot of welded joints.

As shown in Figure 1, the armor grade materials fell within the ASME standard deviation and trend with the mismatch ratios. Therefore, the materials used on the ground combat vehicles behave similarly to standard welded joints and the optimization can proceed.

3. MODELING

A fundamental aspect of this work assumes an accurate understanding of the loading the structure experiences. The load case used for this optimization should represent the most frequently encountered conditions, since fatigue failure occurs after numerous cycle exposures rather than at a single maximum amplitude. For proof of concept, this work looks at a generic v-hull structure with the finite element analysis software Abaqus [2] under static loading, with reactionary forces acting on all four corners, and a central, downward force representing the weight of the engine.

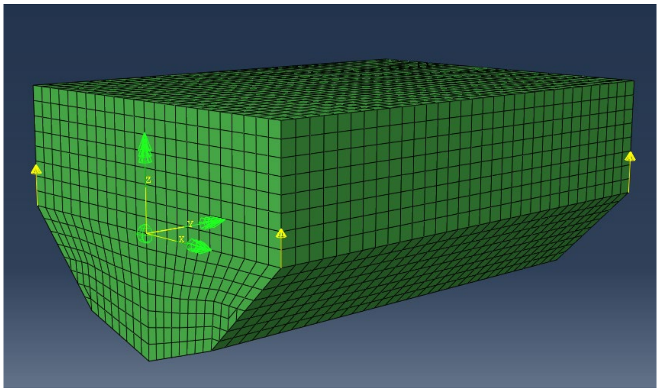

Figure 2. Static loads on a generic v-hull structure.

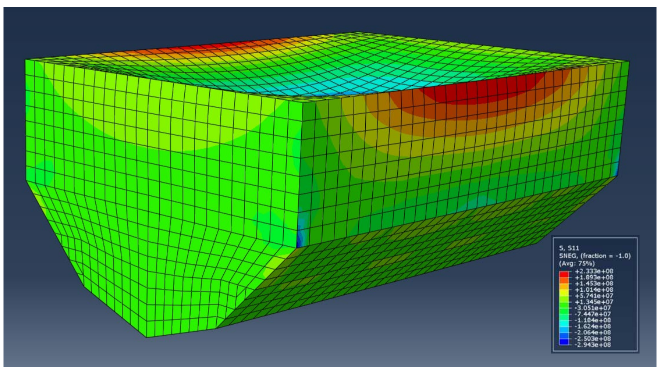

Figure 3. σ_{xx} values.

Each panel is individually analyzed for assembly. Because welds are most vulnerable to failure from opening stress, the optimization considers the σ_{xx} values for the panel running along the length of the vehicle as shown in Figure 3. These stress values from the finite element analysis are used in the stress calculation during the optimization process.

4. OPTIMIZATION

The main objective of the optimization is to maximize the fatigue life of the structure. However, the final recommended assembly plan should not add a burdensome cost, so the cost of the assembly is considered as a second objective in parallel. For the sake of simplicity, each node of the model is considered one foot, making the length of the vehicle 33 feet, within the range of a typical combat vehicle. Nine foot plates assemble the 33-foot panel, meaning that the panel requires three welds along its length.

4.1. Optimization Variables

The fatigue life of the structure is measured as a factor of the maximum encountered stress for each weld. Just as residual stresses as a result of the welding process can be mitigated by best practices, this optimization works to avoid exposing welds to the stresses of the vehicle ‘in-use’ by strategically placing the welds outside of high stress areas. Therefore, position is a continuous variable of the optimization.

The filler material of the weld is considered a discrete variable. Since a vehicle is unlikely to be assembled of varying base metals, the two consumables tested with 12560 are used and their fatigue performance is scaled to the centroid of their distribution along the S-N curve.

The weld type is another discrete variable considered in this optimization. Three commonly used welds, butt, v, and double-v welds, are the options made available for the assembly. The type of weld scales the maximum stress encountered at the selected position by the stress concentration factor (SCF) designated by the IIW [3]. Each SCF is scaled to the lowest performing weld (butt weld).

Each weld type also has an associated cost, based on the Navy’s weld cost model [4]. This model considers the labor and material associated with each weld type per unit length. While this model may not accurately determine the actual cost of assembly of a combat vehicle due to the difference in scale to the Navy, it does provide an accurate comparison of cost between the three weld types, which is the most important factor to the optimization. Again, the three cost factors are scaled to the lowest value.

With all variables (position, weld-type, and filler material) defined, the constraints also need to be laid out. The distance between two welds must not exceed the length of the plate being used to assemble the panel. Additionally, two welds must be no closer than the width of two standard heat affected zones, in order to comply with welding best practices.

4.2. Multi-Objective Genetic Algorithm

Because the optimization needs to consider discrete variables, gradient-based methods are immaterial. Therefore, a genetic algorithm in the mathematical engine known as the Decision Support Toolkit, which can consider discrete variables and multiple objectives, is utilized.

The Decision Support Toolkit (DST) is composed of a GUI where the user defines the optimization variables, constraints, and flow chart of the optimization, and a Solver, which runs external applications (in this case, MATLAB [5] executable files) and analyzes and ranks variable combinations.

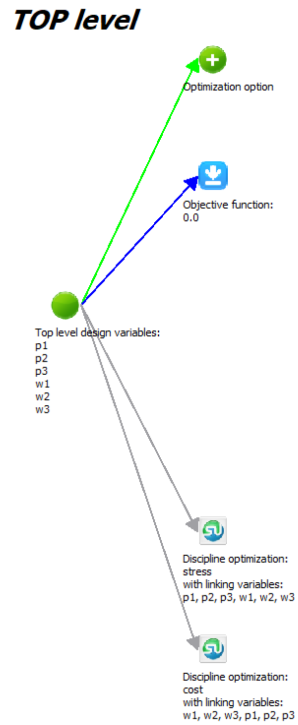

Figure 4. Flow chart of the top level optimization in DST.

The optimization considers multiple objectives by evaluating each objective first (in this case, fatigue life and cost). Now a best-case reference point for each objective feeds into the system level optimization, which then balances the distance between the current evaluation and the best-case evaluations. The optimization is capable of showing preference for one objective over another by assigning a weight to it; however, in this example, cost and stress are considered equally.

System Level Multidisciplinary Optimization

$$\min_{DV_i \quad i=1,\ldots,N} \left(e^{\left(\sum_{i=1}^{N}\left(\frac{Obj^{i\_best}-Obj_i}{PRR^i}\right)^2\right)} \right)$$

subject to:

$$g_i(DV_i) \leq 0 \qquad i=1,\ldots,N$$
$$h_i(DV_i) = 0 \qquad i=1,\ldots,N$$
$$DV_{i_L} \leq DV_i \leq DV_{i_U} \qquad i=1,\ldots,N$$

Figure 5. Description of the system level optimization.

The algorithm generates three welds with associated position, type, and material. The Solver passes these variables into the executable files. The stress evaluation interpolates and pulls the maximum stress encountered at the designated position of each weld from the finite element analysis, then scales each value by the associated weld type and material. Lastly, the maximum value of the three stresses is written into a file which feeds back into the Solver as the evaluation value. The cost is a measure of the weld types selected since each assembly utilizes the same number and length of welds. Additionally, the variance of the distance between each set of positions is calculated, under the assumption that a more evenly spaced panel is cheaper. The total cost value is calculated by weighted factors of type and spacing. The final cost value is sent back from the executable to the Solver in the same manner. The assemblies are ranked by their evaluations. The population and generations numbers (i.e., the number of assemblies evaluated) were increased between runs until a sense of convergence is reached (in this case, when the final generation evaluations were within 10 percent).

4.3. Results

The top ranking fatigue life evaluation sacrifices even spacing to move away from the maximum stress position (at 17 feet) while still meeting the constraints. The stronger weld types are used.

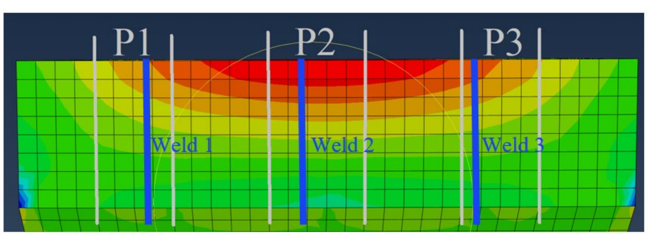

Figure 6. The top ranking fatigue life assembly. Positions 8.89, 15.86, and 24.78, and v, double-v, and double-v welds, respectively.

The top ranking cost evaluation has very even spacing between the three welds and utilizes the cheaper type of welds.

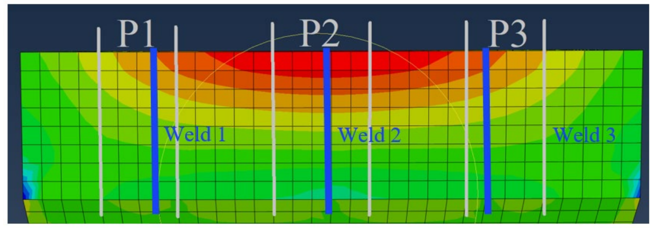

Figure 7. The top ranking cost assembly. Positions 8.16, 16.77, and 24.94, and butt, butt, and v welds, respectively.

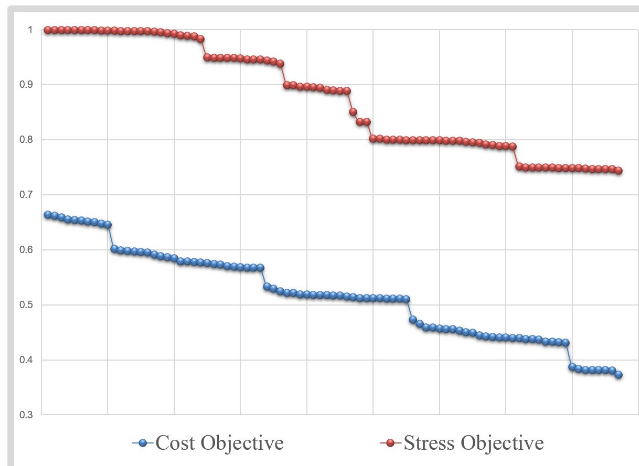

Figure 8. Stess and cost evaluations through the GA.

Finally, the system level evaluation balances the two objectives by only using the strongest, most expensive weld type in the high stress region, and maintains even spacing between the welds.

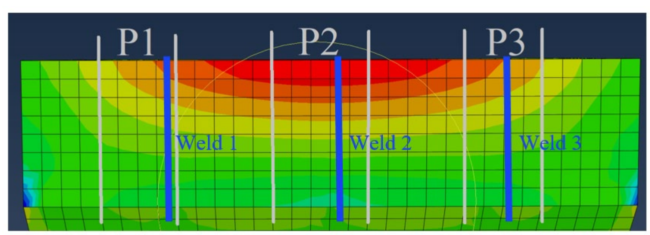

Figure 9. The top ranking system level assembly. Positions 8.78, 17.54, and 26.19, and butt, double-v, and butt welds, respectively.

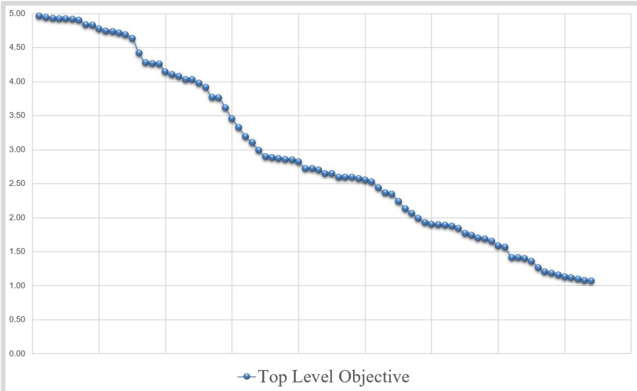

Figure 10. Top level evaluations through the GA.

The optimization proves capable of designing an assembly that minimizes weld stress exposure and therefore maximizing the fatigue life.

4.4. Adding Angularity

The last iteration of this optimization considers adding angularity to the welds along the panel. Each weld now has an associated angle between 30 and 150 degrees in an increment of 10 degrees (30, 40, 50 degrees, etc.). This change in geometry not only allows the weld to avoid areas of high stress, but also changes the magnitude of the opening stress encountered. This requires a stress tensor transformation, but the evaluation still only considers the opening stress.

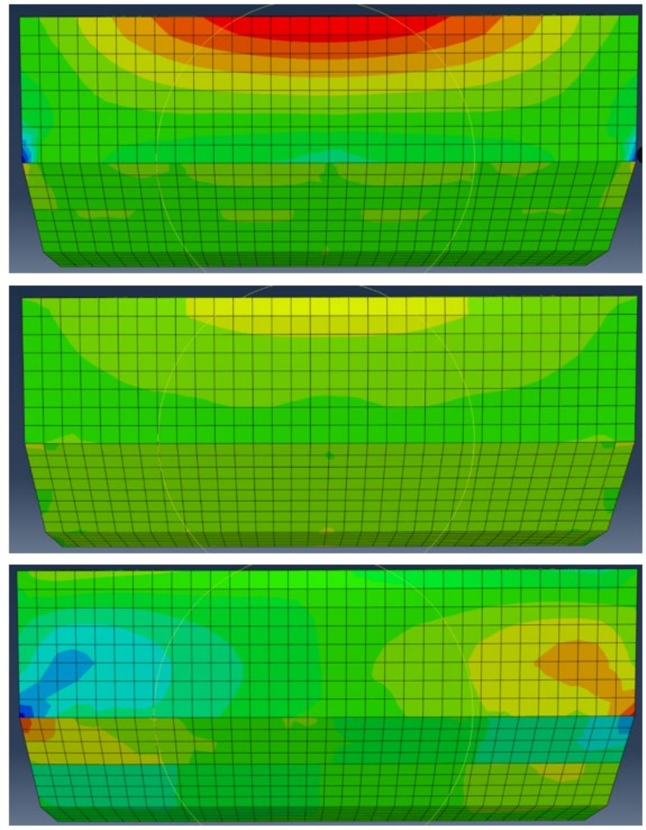

Figure 11. σ_{xx}, σ_{yy}, and τ_{xy} values used in the transform.

The cost evaluation adds a penalty proportionally as the angle moves away from 90 degrees to consider the additional labor and potentially wasted material associated with the angles. Several constraints are added to still ensure no distance between welds exceeds the plate size, and the welds are not allowed to cross over each other.

The addition three variables to each evaluation required an increase in population and generation sizes.

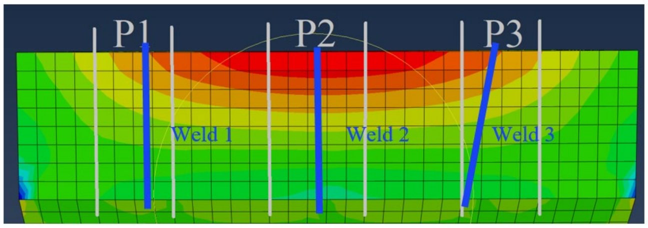

Figure 12. The top ranking system level evaluation including angularity. Positions 7.85, 16.80, 24.02, and butt, double-v, and butt welds, respectively.

While the constraints significantly limit the angularity of the welds, the final result still shows proof of concept. The third weld angles out away from the higher stress. The first weld would violate the constraint if angled away from the stress. The final assembly still indicates the stronger weld type for the high stress region and maintains relatively even spacing.

5. CONCLUSION

By considering the weld's position, type, and material, a structure's fatigue life can be improved from assembly. Cost as a second objective ensures attention to the manufacturability of the structure. Future work includes incorporating multiple load cases. By focusing on the fatigue performance of the structure in the design and assembly stages, the overall availability as well as safety of the vehicle increases.

6. REFERENCES

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