

Weld and Adhesive Optimization Process Development And Implementation on Vehicle Body Structure Development

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ABSTRACT: Passenger vehicle structural performance is extremely sensitive to Welds and Adhesive bonds. Traditionally multi-disciplinary optimization across different disciplines is performed largely with thickness, shape and material grade as variables. The objective of this study was to optimize the spot weld count and linear length of adhesives in the body while balancing vehicle structural performance and weight. Various optimization scenarios were carried out such as a) maintain current structural performance but minimize weld count, adhesive length and body weight, b) maintain current weld count and adhesive length but maximize structural performance and minimize weight, etc. Including welds and adhesives as variables in the Multi-Disciplinary Optimization (MDO) processes provides additional design space to improve structural performance and reduce cost through spot weld and adhesive minimization.

This paper presents an automated Weld & Adhesive Optimization process developed at FORD to improve vehicle structural performance using a unique parametric technique developed by DEP, Inc. Variables include weld pitch and its alternative forms such as number of welds in a given weld line and % change to the weld count, type of welds, layers of adhesive bonds and adhesive bond dimensions. This process was implemented successfully on a passenger car currently in production with the primary objective to increase modal frequency separation between body-in-prime bending and torsional modes while maintaining the current number of total welds in BIP structure. Majority of the design variables were weld parameters at rocker, front and rear rails, roof liners, seat cross members, roof bows and sled runner locations. Parameters were automatically created using DEP's Meshworks software. It generates weld/adhesive lines automatically once parts are identified. Variables are created quickly and Design of Experiments (DOE) techniques are used to generate multiple designs by integrating the parametric model with Isight. Over 1000 designs were generated rapidly & automatically and evaluated across functions and attributes. Scripts were created for automatic post processing of results. Subsequently, an input-output matrix was tabulated and Response Surface Models (RSM's) were created using Isight's RBF tool. Isight's Pointer Algorithm was set to determine the optimal solution. The validated optimal design showed the required frequency separation with optimal placement of welds and adhesives. This process is a key enabler to execute weld and adhesive optimization with minimum resources to achieve optimum number of welds, placement of the welds, and adhesive length in a fast turnaround time demanded by current product development cycle.

1. INTRODUCTION

Parametric CAE models are an essential part of any MDO process. For complex vehicle Crash, NVH and Durability models the typical parameters that are considered are a) shape, b) gage, c) features and d) materials. Connector elements such as spot welds, seam welds and adhesives are typically not considered as design variables. By adding them to the MDO process the design space can be further expanded.

During early stages of the vehicle development when maximum design space freedom is available all of the above categories of design variables can be used for parameterization and subsequent optimization. However, as the vehicle development progresses towards the final design freeze the design space reduces. For example, once the styling theme and vehicle packaging stages are completed there is very limited applicability of shape parameters. Close to the end of the development cycle the design variables used for MDO are primarily the gage, grade or connectors such as spot welds, seam welds and adhesives.

Even at the tail end of the vehicle development process the performance of the vehicle body can be increased while maintaining the weight targets by optimally placing the spot welds and adhesives at the right locations. Further, for a given

level of performance the number of spot welds and amount of adhesives can be minimized which can significantly reduce manufacturing costs.

In this paper only spot welds and adhesives have been addressed as design variables and their impact on vehicle performance especially body static torsion and dynamic torsion and weight have been assessed. DEP's Meshworks software has been used to create weld/adhesive parameters using a unique weld/adhesive line methodology. The MDO process developed and its application to a vehicle program are discussed in detail.

2. WELD & ADHESIVE OPTIMIZATION PROCESS DETAILS

2.1 Design of Experiments (DOE) based Optimization

The weld and adhesive optimization developed is depicted in Figure 1. Following are the important steps of this process:

- Full vehicle stiffness, crash, NVH and durability models are required at the start of the process. Depending on the load cases that are to be considered for optimization, all or some of the above models will be used for subsequent parameterization.

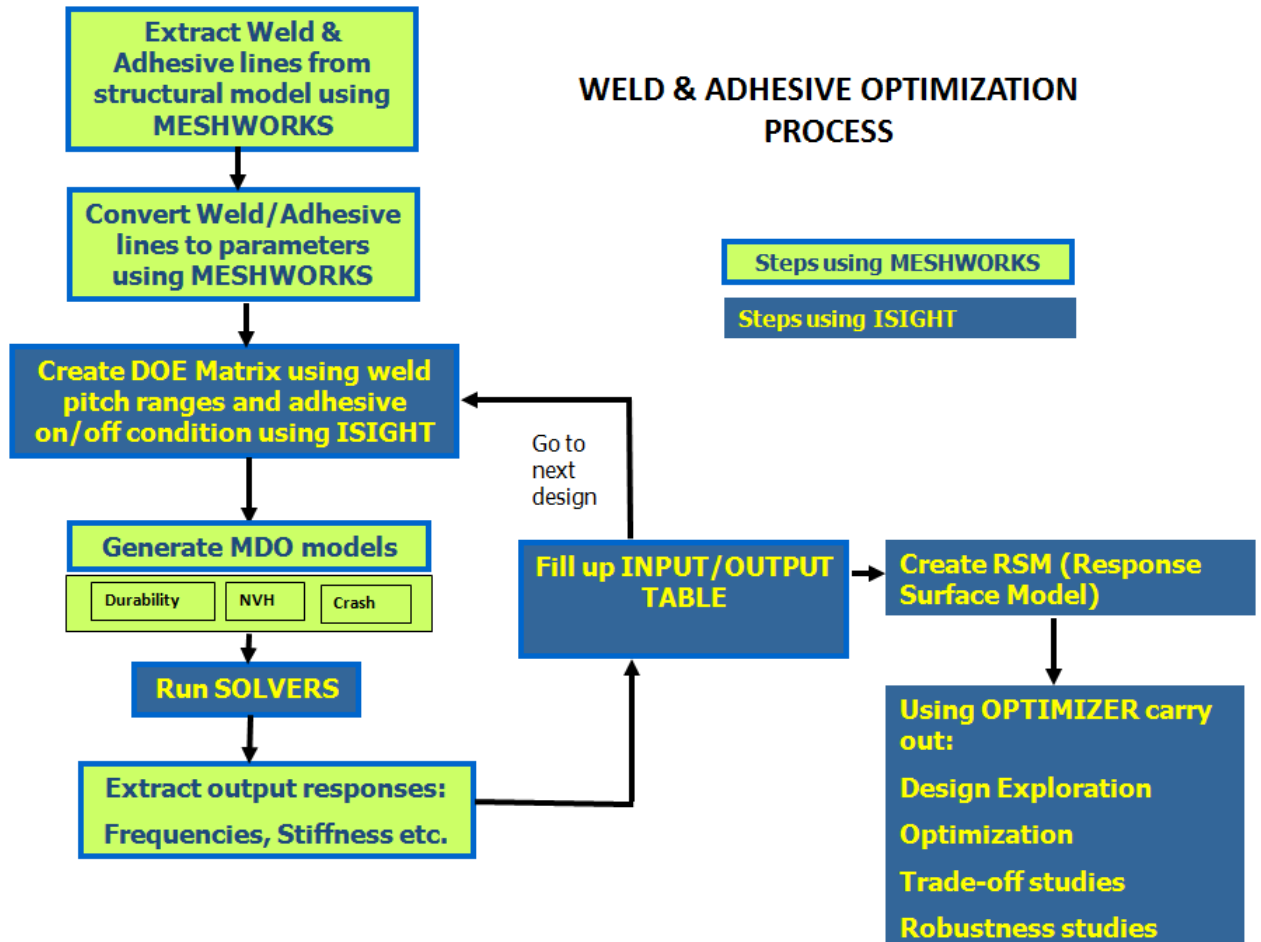
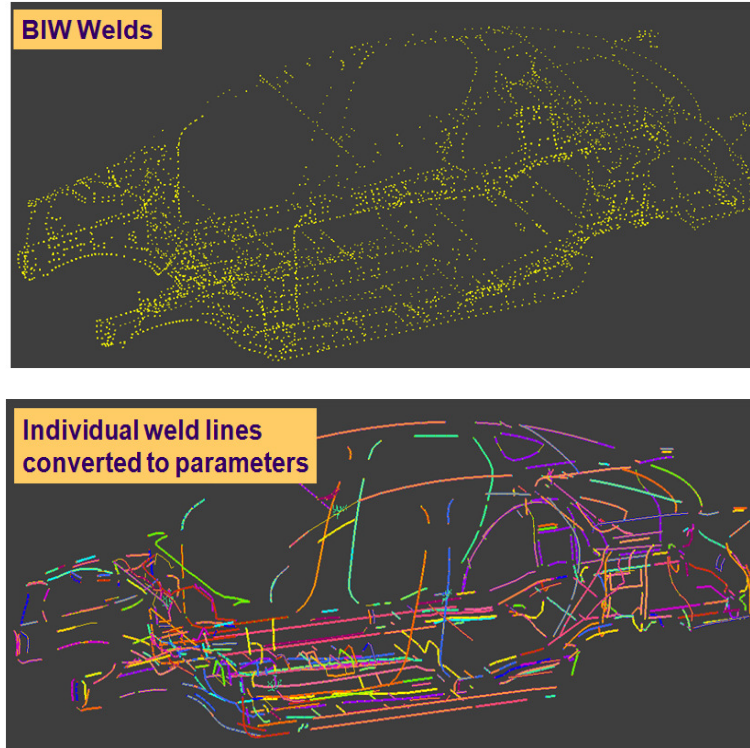


Figure 1

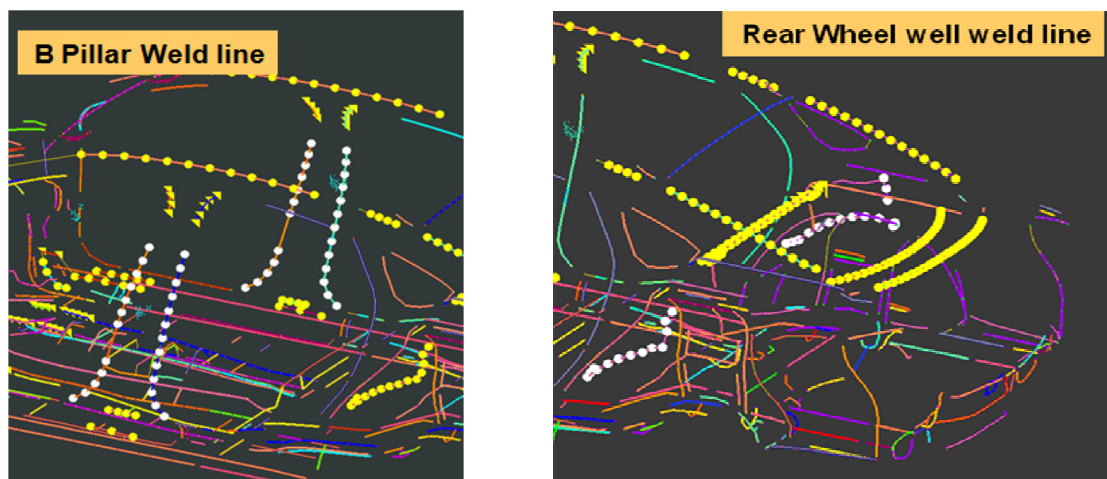
- Using MESHWORKS the discrete spot welds are converted automatically into weld lines. The automated weld line creation takes into account parts that are welded together (both 2t and 3t) and whether they are at the flanges of the parts or in their interior. Other factors taken into account are a) the relationship between the connecting part thicknesses and the weld nugget size and b) the relationship between connecting part thicknesses, part materials and the weld failure forces. Figure 2a shows the typical spot welds in the body-in-prime of the vehicle. Figure 2b

shows how the selected spot welds are automatically converted to weld lines. Besides creating weld lines using existing welds, there are other ways to create weld lines from CAD curves and 1D geometries as well.



Figures 2a & 2b

- Using MESHWORKS the above generated weld lines are then converted into parameters whereby the number of spot welds in each weld line can be varied with the following methods, a) spot weld pitch varying over a minimum to a maximum value within a weld line, b) spot weld pitch of a group of weld lines being varied as a percentage of their original value, c) explicitly the weld count in each weld line varying over a minimum to a maximum value. Using these methods there is complete flexibility in generating a spectrum of parameters ranging from making every weld line as an independent parameter to making all the weld lines into one single parameter. Figures 3a and 3b show welds created with different pitches (or count) at different locations of the vehicle body structure.



Figures 3a and 3b

- Adhesive lines are created in a similar fashion. Adhesive lines are created using the following methods, a) existing adhesives can be converted automatically to adhesive lines, b) existing weld lines can be used to create adhesive lines at the same locations and c) using CAD curves and 1D geometries.
- Adhesive lines are then automatically converted to adhesive parameters whereby they take on a binary setting of whether to create adhesive elements or not when activated. When an adhesive parameter is defined the width, thickness and material property of the adhesive are all specified as additional inputs. Further, the number of elements along the length, width and thickness of the adhesive are all specified as meshing conditions. Figures 4a and 4b show adhesive lines and their activated state respectively. Just as the weld parameters, there is complete flexibility in generating a spectrum of parameters ranging from making every adhesive line as an independent parameter to making all the adhesive lines into one single parameter.

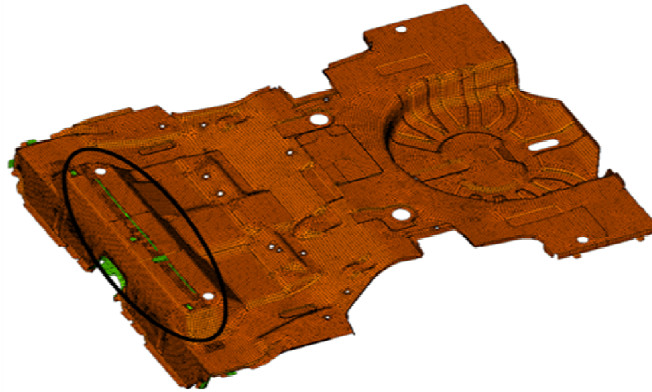


Figure 4a – Adhesive Line

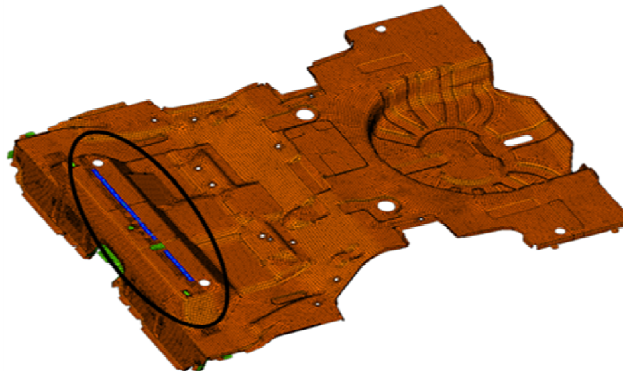


Figure 4b – Activated / Realized Adhesive Line

- Using Isight a Design of Experiments (DOE) matrix is generated considering the weld variables and their ranges and the adhesive variables and their 'on-off' settings.
- For every design in the DOE matrix MESHWORKS automatically generates runnable structural FE models for Crash, NVH and Durability with weld elements with appropriate pitch and adhesive elements.
- The models thus generated are then automatically submitted for solver runs such as Nastran, Abaqus and LS-Dyna (depending on the load case) in the High Performance Computers (HPC).
- All output responses such as body-in-prime (BIP) torsional and bending stiffness, BIP frequencies, trimmed body frequencies etc. are automatically extracted from the solver output files and tabulated as an Input-Output (I/O) table.
- The above two steps of job submission and results extraction have been highly automated through Ford custom scripts.
- Chances are high that one or more designs with better performance (or alternately with reduced weld count but with baseline design performance) could be obtained from the I/O table of the DOE runs. To get to the true optimum, approximation models using 'Response Surface Modeling' (RSM) techniques are created using the I/O table. The RSM will then provide sensitivities of the structural performance to various weld & adhesive lines.

- Using the sensitivities obtained through the RSM, several optimization scenarios with appropriate objectives and constraints can be set up using Isight to arrive at the final optimum. Typical optimization scenarios carried out are as follows:
 - Set objective as improvement in performance while setting constraints on weld count and adhesive lengths
 - Set objective as minimize weld count and adhesive length while setting constraints as maintain baseline design performance

2.2 Spot Weld Topology Optimization

Other than the DOE based weld & adhesive optimization process mentioned in the above section, a unique Meshworks driven Topology Optimization process can also be used for minimizing the weld count while maintaining the baseline design performance. Below are the important steps of this process:

- The spot weld lines created using the process mentioned in the previous sections are realized with a pitch of 5mm thereby producing densely packed weld elements next to each other. These spot weld hexa elements with 5mm pitch represent the design space for topology optimization. Rest of the model is considered as non-design space.
- Topology optimization is carried out with this model whereby constraints are set on frequencies, static stiffness etc., while the objective is to minimize material in the design space, which in this case is the densely packed weld elements.
- The optimization will result in varying density design space elements indicating their effectiveness vs. in-effectiveness. Using these results and some manual fine tuning the final location of spot welds are arrived at.

3. WELD/ADHESIVE MDO PROCESS APPLIED TO VEHICLE PROGRAM

3.1 Weld Optimization on trimmed body for mode separation

- The optimization process explained in previous sections is used on a sedan to improve its modal performance.
- Objective of the study is to separate the trimmed body vertical bending mode & torsion mode as much as possible from the baseline level of 0.1Hz, by maintaining or increasing the weld count. Figure 5 shows the frequency separation of baseline trimmed body.

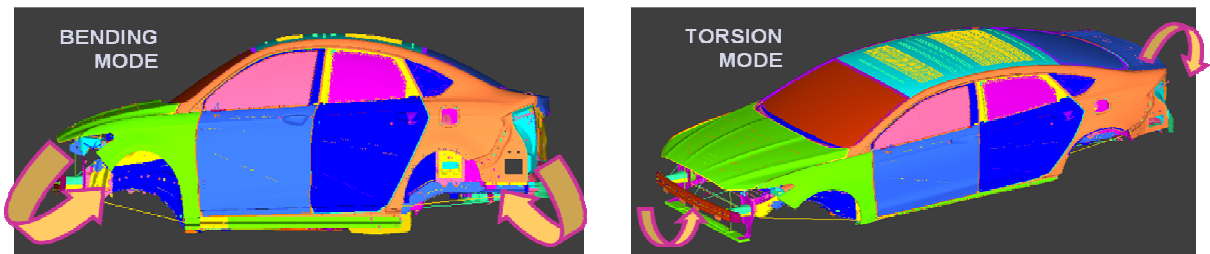


Figure 5 – Baseline Mode separation of 0.1Hz

- The parametric methodology (described in section 2) developed by DEP was used in optimizing the vehicle body structure's performance using spot weld pitch as design variable. Spot weld lines were created & parameterized instantaneously, with ease using MESHWORKS software.
- DOE based optimization was performed using Isight and a mode separation of 0.4Hz was achieved with a small increase in the number of spot welds. This is an appreciable improvement from the baseline design separation of 0.1Hz considering the fact that it is done at the trimmed body level.
- Isight helped to rank order the spot weld lines based on sensitivity to the global trimmed body modes.

3.2 Adhesive optimization to improve Body-in-Prime (BIP) performance

- The adhesive optimization process explained in the previous section is used to improve the performance of the sedan BIP.
- Objective of this study is to improve the baseline BIP performance in terms of global mode frequencies & static stiffness by adding minimum number of adhesive bonds.
- The spot weld lines at the 10 most sensitive locations were selected based on the rank ordering obtained from the DOE based optimization explained in section 3.1. Adhesive lines and realized adhesive bond elements were created at these 10 locations automatically using the baseline BIP model. Figure 6 shows the adhesive bonds added.

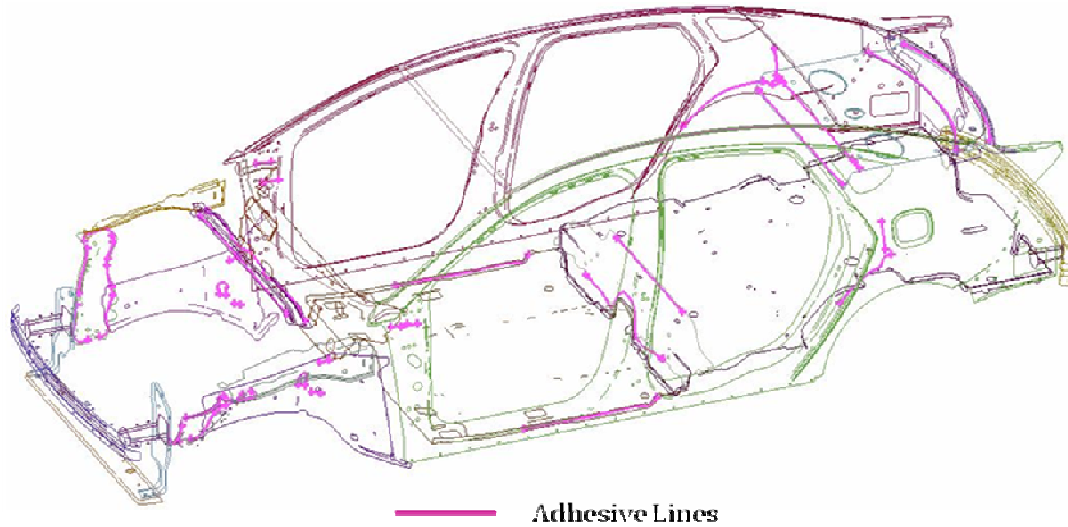


Figure 6 – Adhesive Locations

- Tables 1 & 2 show the improvement in BIP performance of the model where the adhesive bonds have been added.

S.No	Global Modes	Frequency Change (Hz)
1	Front end Vertical Bending	+ 0.1
2	Rear end Vertical Bending	+ 0.0
3	Global Torsion	+ 0.3
4	Second order Vertical Bending	+ 0.1

Table 1

S.No	Static Stiffness	% Change
1	Bending Stiffness (N/mm)	+ 0.3
2	Torsion Stiffness (kNm/rad)	+ 0.6

Table 2

- The results clearly indicate an appreciable performance improvement by adding adhesive bonds at mere 10 locations as suggested by the DOE based optimization.

3.3 Spot Weld Topology Optimization on Body-in-Prime (BIP)

- The topology optimization process explained in section 2.2 has been applied on the sedan BIP.
- Objective of this study is to minimize the spot weld count by maintaining the baseline BIP performance in terms of global mode frequencies & static stiffness.
- Spot weld lines were created automatically from the discrete spot weld points on the flanges using DEP's MESHWORKS software as shown in Figure 7.
- These spot weld lines were realized with a weld pitch of 5mm to generate the design space. Figure 8 shows the spot weld based design space in the BIP and also enlarged views of local regions.

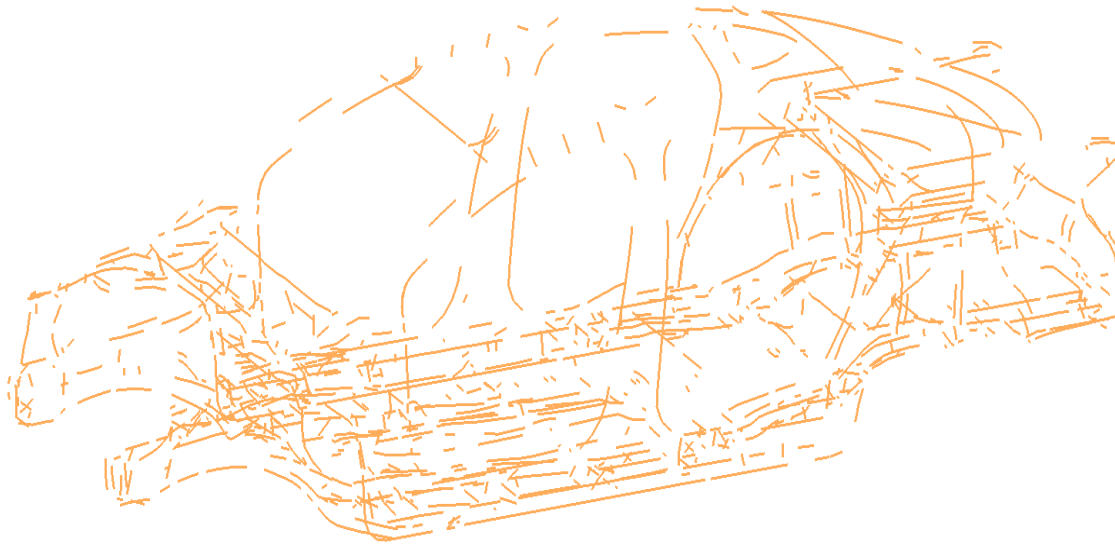


Figure 7 – Auto generation of Spot weld Lines

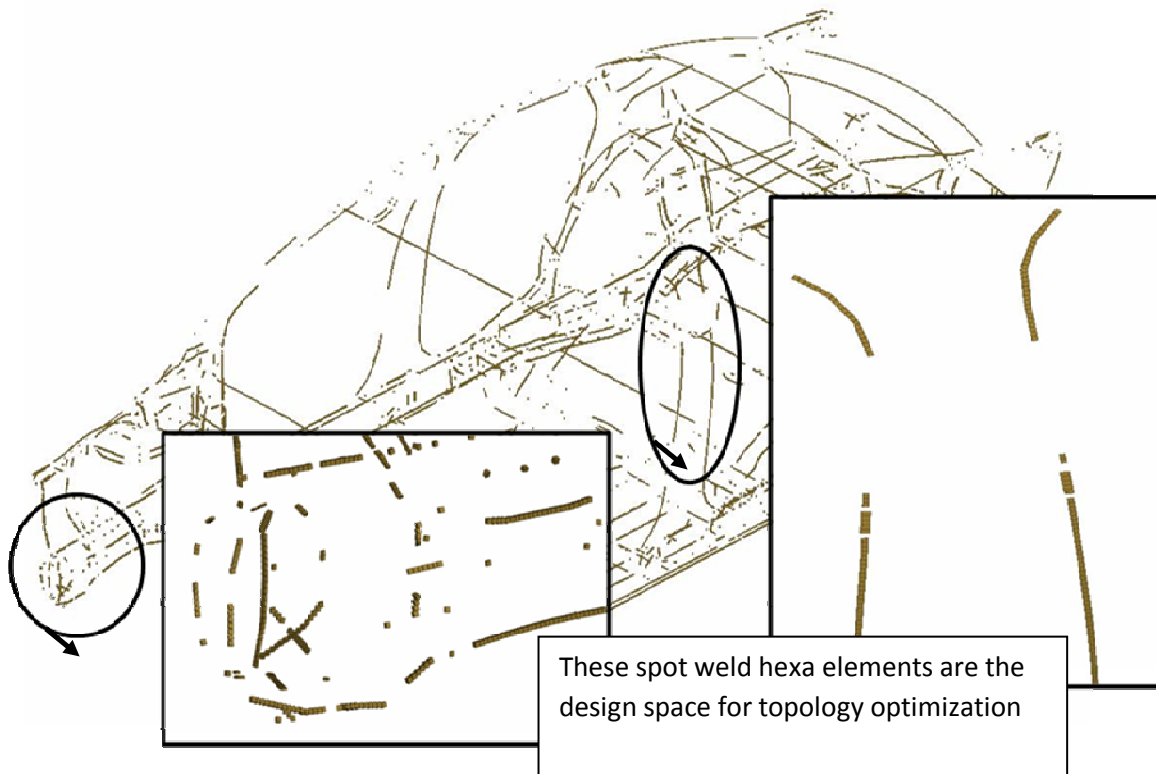


Figure 8 – Spot weld hexa elements with 5mm weld pitch

- Spot weld hexa elements were used as the design space and frequencies of BIP global modes and static stiffness values of the baseline design were used as constraints. The objective is to minimize the volume fraction of spot weld hexa elements.
- Based on the topology optimization results, areas with high sensitivity to performance (smaller weld pitch) and areas with low sensitivity to performance (larger weld pitch) were automatically identified. Manual fine tuning of the weld pitch was carried out using the topology results to arrive at the final design which resulted in a non-uniform weld pitch. Figures 9 & 10 show the change in the spot weld locations in specific regions of the BIP between baseline design, 5mm pitch design space model & Optimized design.

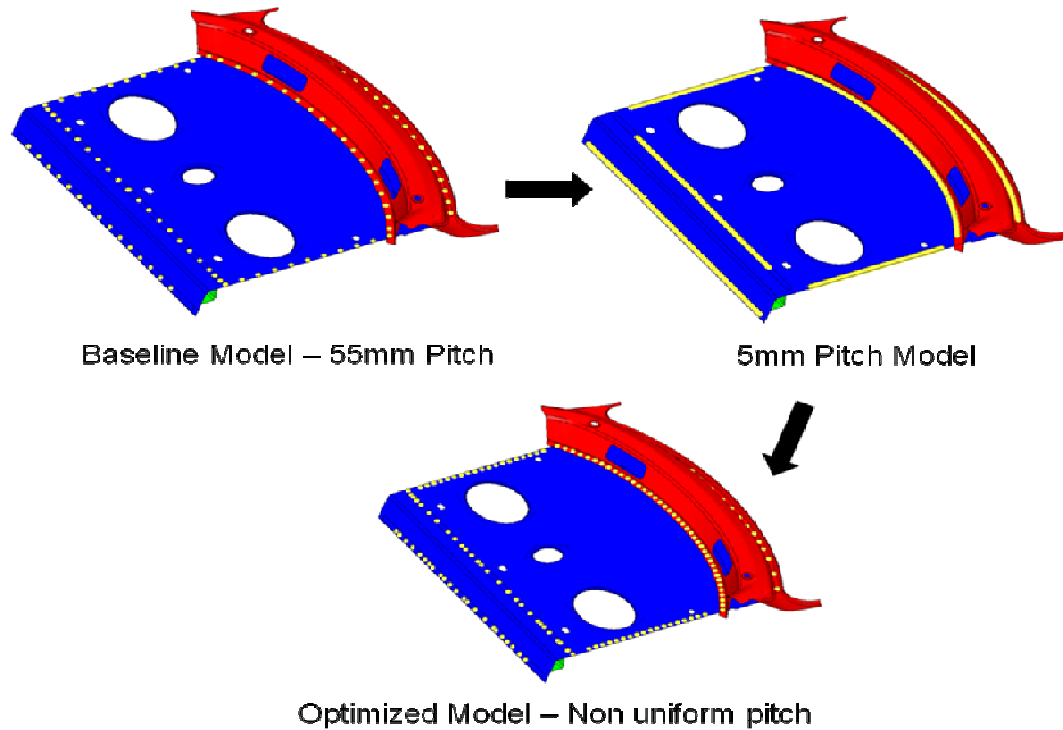


Figure 9 – Spot weld pitch comparison

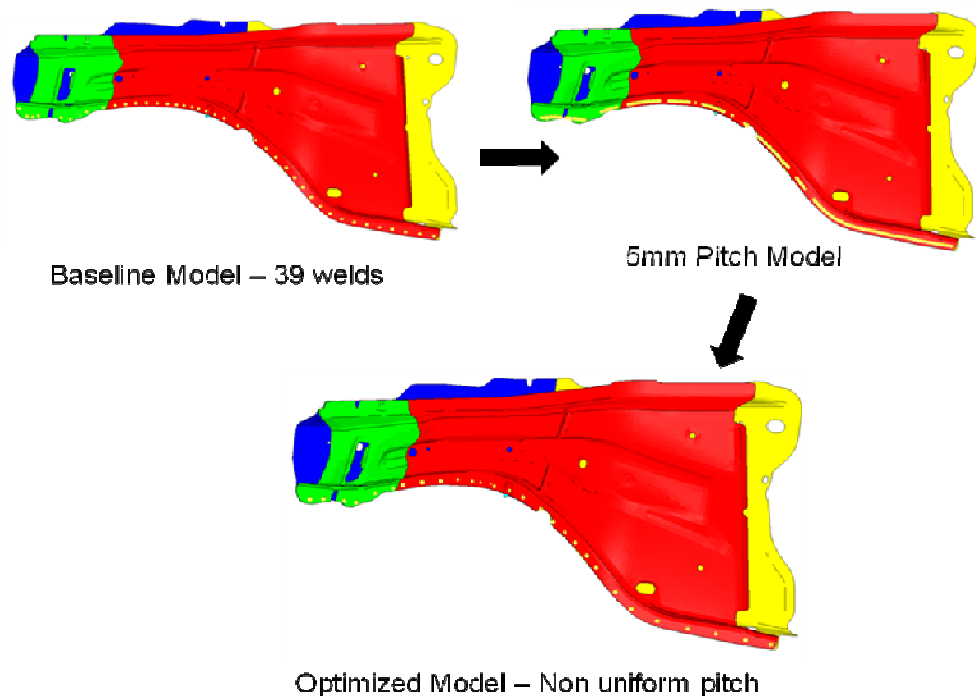


Figure 10 – Spot weld pitch comparison

- Identified opportunity to reduce 268 spot welds while at the same time improving the structural performance of the BIP structure.
- Table 3 & 4 show the improvement in BIP performance of the optimized design as compared to baseline design.

S.No	Global Modes	Frequency Change (Hz)
1	Front end Vertical Bending	+ 0.1
2	Rear end Vertical Bending	+ 0.0
3	Global Torsion	+ 0.5
4	Second order Vertical Bending	+ 0.6

Table 3

S.No	Static Stiffness	% Change
1	Bending Stiffness (N/mm)	+ 1.0
2	Torsion Stiffness (kNm/rad)	+ 0.2

Table 4

- Results clearly indicate the ability of the spot weld topology optimization process to minimize welds while at the same time improve structural performance.

4. CONCLUSIONS

- DOE and topology based weld and adhesive optimization processes for spot weld and adhesive length minimization while balancing performance have been developed and implemented in vehicle programs.
- This process was implemented successfully on a passenger car currently in production with the primary objective to increase modal frequency separation between vehicle body bending and torsional modes while optimizing the number of welds and adhesive locations in the structure.
- Weld & Adhesive optimization processes proposed in this paper can be used for different optimization scenarios such as:
 - Improve current structural performance while setting constraints on weld count and adhesive lengths
 - Minimize spot weld count and adhesive lengths while maintaining current structural performance
 - Improve structural performance and minimize spot weld count and adhesive lengths simultaneously
- This process can be used at any stage of the vehicle development. Even at the late design freeze stages when all other forms of design parameters such as shape, gage etc. cannot be altered, weld and adhesive optimization can be carried out to improve structural performance and reduce manufacturing cost.
- As shown in the paper, the spot welds with the addition of adhesive bonds at critical areas will improve the body performance with little to no weight addition.
- Manufacturing cost savings by way of reduced spot weld count and minimized adhesive lengths could be truly significant.
- DEP's MESHWORKS software described in this paper helps in generating the spot weld & adhesive bond lines with minimal complexity & parameterize the entire BIP very rapidly.
- Even though this paper addresses the optimization processes with respect to NVH performance of the body, they can be naturally applied to other attributes such as Safety & Durability and also for Multi Disciplinary Optimization (MDO).

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