

Optimisation of Welds with Manufacturing Considerations

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Abstract: Fatigue is the main in-service failure mode for automotive chassis & suspension parts, especially weld fatigue. Over the years, Tata Steel Automotive Engineering (TSAE) has developed techniques for CAE durability assessment including the optimisation of seam-welded chassis/suspension structures. Seam weld optimisation at TSAE has previously been based on a constant weld length and constant gap between welds for each weld run. This method has two drawbacks; weld patterns generated are regular in nature, reducing the flexibility to position welds where they are most effective and excessively short welds are often left at the end of a run of welds. The objective was to develop an improved optimisation technique using Isight that always produced a manufacturing feasible design and allowed more flexible and irregular positioning of welds. Manufacturing constraints considered were minimum weld length, minimum gap length and minimising the number of start/stop operations.

To reduce the number of design variables, a new load-case-weighted optimisation scheme was developed using a single weighting factor for each load case. These factors were used to generate weld patterns by scaling the strain energy density in finite elements from an initial fully welded design. Weld elements were selected for retention/deletion by comparing a weighted sum across all load cases with a threshold value. During each optimisation, Isight varied the weighting factors as “design variables” to minimise overall weld length, while achieving stiffness and fatigue life targets. The process has been extended to function for laser weld designs where an intermittent weld pattern is generally the most effective.

Keywords: Design Optimisation, Fatigue, Fatigue Life, Minimum-Weight Structures, Optimisation, Seam Welding, Welding, Automotive Chassis, Automotive Body, Steel.

1. Introduction

Researchers and engineers have found that, gauge for gauge, there is often little difference in the fatigue performance of welded conventional mild steel joints and welded Advanced High Strength Steel (AHSS) joints, for similar welding processes and weld quality, e.g. metal active gas (MAG) welding (Lewis, 1996). In other words, fatigue performance of welded thinner AHSS structures may become poorer. Consequently, in order to ensure full mass-saving potential of AHSS grades, more rigorous assessments of weld fatigue performance and optimisation of weld placement have become an important parts of any new vehicle development.

To significantly speed up the selection of weld placement for best durability and stiffness performance, Tata Steel Automotive Engineering developed an effective stitch weld optimisation tool (Wooffindin, 2007). This started with a fully welded model and then deleted weld elements until an optimal solution was found. The welds in the model were broken down into weld zones. Each zone was assigned two parameters, an individual weld length and a gap length between welds as shown in Figure 1. These parameters were optimised to achieve a minimum total weld length while achieving the desired fatigue-life target and ensuring that stiffness and strength targets were met. Tata Steel is continuously striving to improve its technology offering leading to a decision to improve the performance of the weld optimiser further.

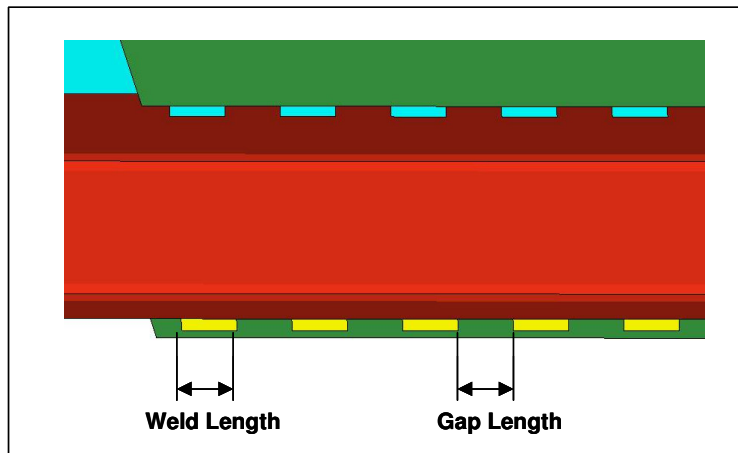


Figure 1. Weld Definitions

Limitations of the previous weld line optimiser were:

- Each weld run has to be a regular pattern
- Weld will always be placed at the start of a weld zone. The start of the zone is dependent on the initial definition of the weld zone.
- Short welds can result at the end of a weld zone
- The number of variables to optimise (weld length and weld gap for each zone) can become too large to optimise effectively in large models

The objective was to develop a new optimiser to produce a manufacturing feasible design including the following features:

- Position weld where it is most effective
- Use strain energy density to provide Isight with engineering knowledge
- Ensure manufacturing constraints (e.g. minimum weld length) are respected
- Reduce the number of design variables
- Maintain capability to optimise for fatigue

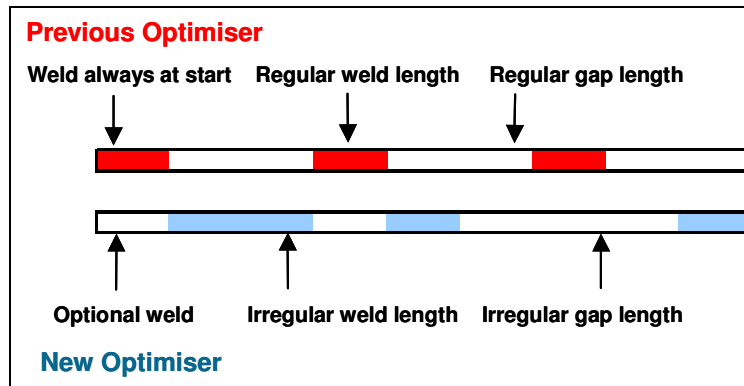


Figure 2. Comparison of Optimiser Features

A comparison of the features of both optimisers is illustrated in Figure 2. The new optimiser will always respect the defined minimum weld and gap lengths.

2. Finite Element Model and Fatigue Analysis

Tata Steel has validated the new optimiser on a variety of vehicle body and chassis components. To demonstrate the technique clearly, a simple representative laboratory test component is used in this paper to demonstrate the new weld optimisation procedures. Figure 3 shows the finite element model used to evaluate the weld optimisation process. This test sample is being used to assess the benefits of laser-MAG hybrid welds in terms of fatigue life. It is planned to subject the optimised weld patterns to physical fatigue tests.

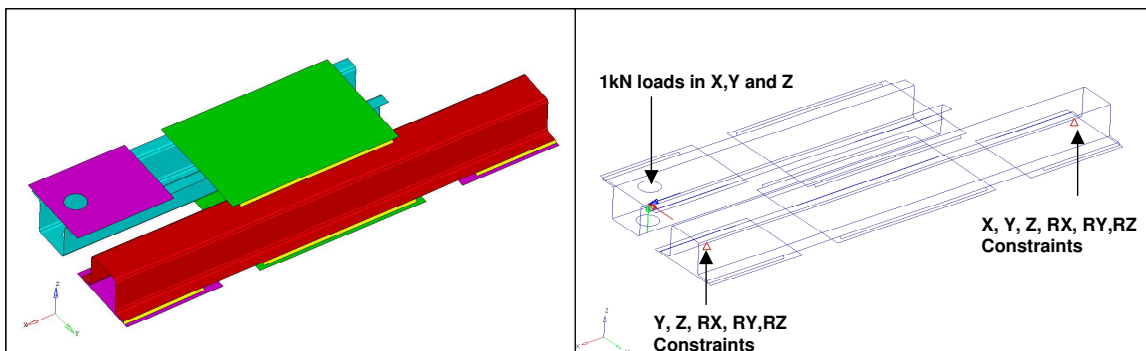


Figure 3. Finite Element Model

The baseline analysis of the ‘fully’ welded design included stiffness analyses and fatigue analysis.

Loads were applied in each of the X, Y and Z directions, as shown in Figure 3, in separate stiffness load cases. Prior to the optimisation, a fully welded finite element model was run and the strain energy density results collected for the weld elements for each load case.

The seam weld fatigue life analysis is based on the “structural stress” based approaches (Fermér, 1998), (Dong, 2001), which suit automatic processing of fatigue lives by CAE software codes. Tata Steel, working closely with its customers, has been able to evaluate and compare the “structural stress” technique against experimental results. More importantly, “structural stress” based weld fatigue data relevant to the welding processes used for automotive and yellow-goods vehicle manufacture have been generated by Tata Steel to improve life assessment accuracy.

For the current laboratory test component, both metal and weld fatigue analyses were performed for loading in the Y direction, with a load range of 1.0 to 10.0kN, using the “crack initiation” and the “seam weld” algorithms available in MSc/Fatigue. Fatigue lives were calculated using fatigue property curves generated from weld and parent metal coupon tests at Tata Steel. The results of the stiffness and fatigue analyses were used to set the targets for the optimisation study.

3. Seam-Weld Pattern Generation

A bespoke tool command language (Tcl) program was written to generate weld elements based on the strain energy distribution in the ‘fully’ welded model. The inputs for this program are a weighting factor for each load case, the base strain energy distribution and element connectivity information.

The first part of the seam welding process is to generate strain energy density vectors for the weld elements in the baseline model. The vectors are normalized for each load case by dividing the energy density in each weld element by the maximum energy density across all of the weld elements. The normalized vectors are stored in a comma separated variable (.csv) file to be read in by Isight.

Weld path information is extracted from Hypermesh using a Tcl macro, so that the weld generation program understands the connectivity of weld elements within the finite element model. Two nodes at one end of the each weld line are selected in turn by hand. The macro then gathers the element IDs and length of each weld element along the individual weld paths. The macro only needs running once prior to the optimisation and will work with different analysis codes / base models. It is also able to cope with continuous weld loops as in the case of welding round a tube.

Table 1. Example Weighted Sum Calculation

Worked example	Normalised Strain Energy Density		Factored Strain Energy Density		Threshold = 0.25
			$f_1=0.6$	$f_2=0.5$	
Element ID	Load Case 1 (W_1)	Load Case 2 (W_2)	Load Case 1 ($f_1 \times W_1$)	Load Case 2 ($f_2 \times W_2$)	Weighted Sum (S)
1955	0.4650	0.0056	0.28	0.00	0.28
1956	0.1460	0.0042	0.09	0.00	0.09
1957	0.1090	0.0037	0.07	0.00	0.07
1958	0.0714	0.0023	0.04	0.00	0.04
1959	0.0743	0.0015	0.04	0.00	0.05
1960	0.0833	0.0200	0.05	0.01	0.06
1961	0.1167	0.0400	0.07	0.02	0.09
1962	0.2440	0.0015	0.15	0.00	0.15
1963	0.3180	0.0023	0.19	0.00	0.19
1964	0.4350	0.0037	0.26	0.00	0.26
1965	0.2660	0.0042	0.16	0.00	0.16
1966	0.2110	0.0056	0.13	0.00	0.13
1967	0.2170	0.0074	0.13	0.00	0.13
1968	0.2220	0.0200	0.13	0.01	0.14
1969	0.2170	0.0200	0.13	0.01	0.14
1970	0.2110	0.0091	0.13	0.00	0.13
1971	0.3860	0.0200	0.23	0.01	0.24
1972	0.9333	0.1000	0.56	0.05	0.61
1973	0.6500	0.0600	0.39	0.03	0.42
1974	0.5333	0.0118	0.32	0.01	0.33

Table 1 shows the method of calculating a weighted sum for each element in the seam weld pattern generation process. The weighted sum is calculated in accordance with the formula below:

$$S = \sum_{i=1}^n W_i \times f_i$$

where:

- W_i is normalized strain energy density for load case 'i';
- f_i is weighting factor for load case 'i';
- n is the total number of load cases selected for optimisation
- S is weighted sum of strain energy density;

In the particular case of element 1955, the weighted sum S_{1955} is calculated as follows:

$$S_{1955} = 0.465 \times 0.6 + 0.0056 \times 0.5 = 0.28$$

Once calculated, the weighted sum is compared with a threshold value chosen by the design analyst. The value of the threshold is set to a value that will produce reasonable weighting factors. Its value is not too important as changing the threshold will change the weighting factors to achieve the optimum design, but not the design itself. Obviously, a value greater than zero is required to prevent all of the weld elements being selected irrespective unless all the weighting factors are zero too. Before running the entire optimisation loop, it is worthwhile to run the weld generation part to discover the relationship between the weighting factors and the total weld length. A design of experiments study is also useful to enable sensible limits to be set for the weighting factors during optimisation.

From Table 1, any weld element with a weighted sum above the threshold value of 0.25, is kept (green) in the model to go to the next optimisation round. A second pass of the weighted sums is made to apply manufacturing constraints. In this example, the allowed minimum weld length and the minimum gap length are both equal to the length of four elements. The first process is to achieve minimum weld length by adding neighbouring elements shown in yellow to runs of green elements shorter than four elements. Secondly, weld gaps shorter than four elements shown in magenta are also filled in. The rest of the weld elements are deselected, and become weld gaps. The weld generation program is called during each optimisation loop by a Simcode object within Isight.

4. Laser Weld Pattern Generation

Laser welding presents a different manufacturing issue to seam welds. Laser welds are often used in vehicle body structures as a replacement for spot welds and tend to be of a constant length. There are different styles of laser welds, some in the shape of a C for example, which are not explicitly covered, but the positioning of a linear weld should hold true for a shaped weld. In addition, inspection of the linear welds is made simpler if they are all the same length.

In the current weld optimisation development, the laser weld pattern generation process was adapted from the seam weld pattern generation scheme. Instead of defining a minimum weld length, a constant weld length was used together with a minimum gap length. To promote an intermittent weld pattern, the weighted strain energy density values were summed over a group of elements until the threshold value was reached. Initially, welds were put at end of each section as shown (red) in Figure 4. Secondly, the Tcl program algorithm shuffled each weld in its section until the strain energy in the weld was maximised (magenta). Finally, welds were repositioned if the gap between welds was insufficient to respect the minimum gap requirement (green). The adoption of a constant weld length facilitated the shuffling of welds.

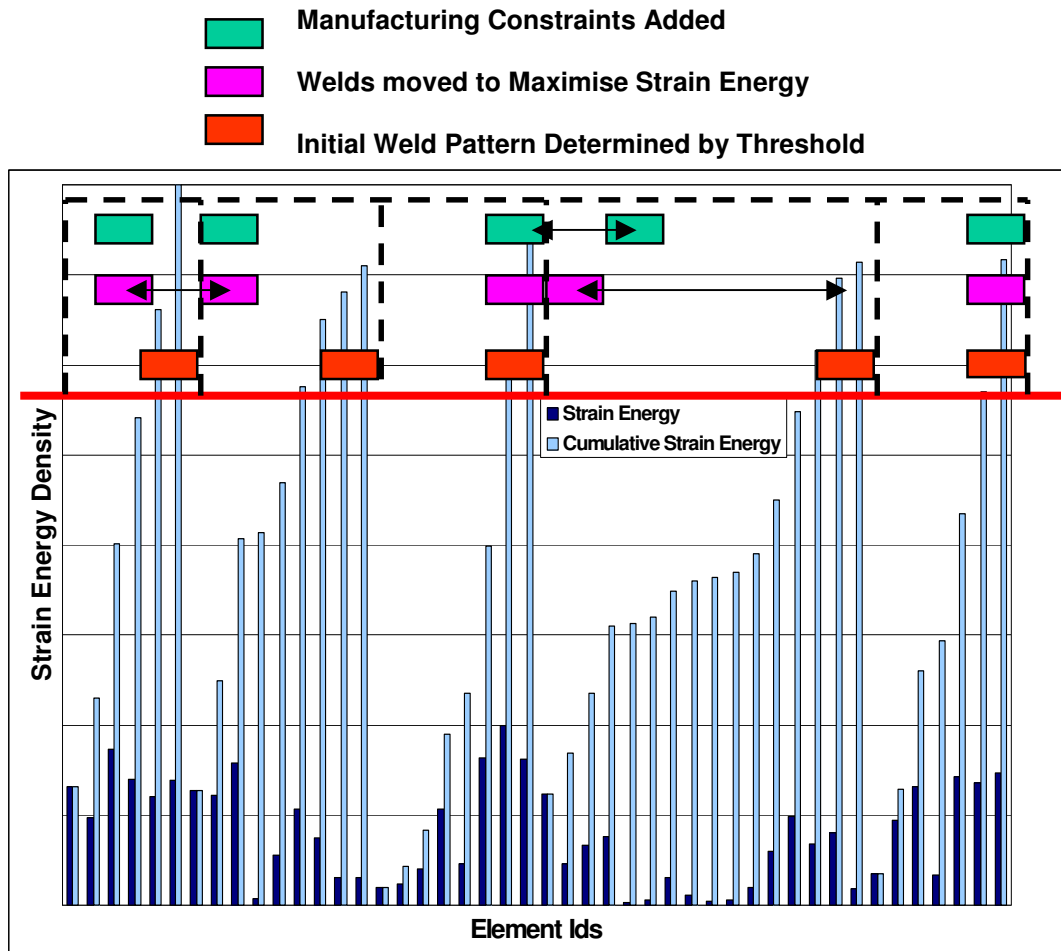


Figure 4. Demonstration of Laser Welding Process

5. Isight Optimisation Set-Up

The high level workflow in Isight is the same for the seam and laser weld processes and is shown in Figure 5. The 'Generate weld elements' object calls a different Tcl program for each of the welding methods.

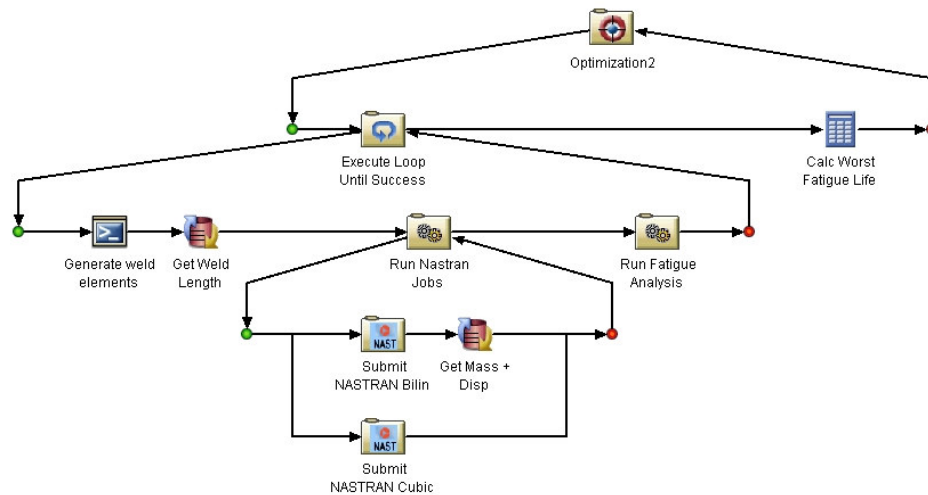


Figure 5. Isight Optimisation Workflow

The constraints for the optimisation were set to a maximum deflection of 1.5mm when a load of 1kN was applied in the Z direction and a minimum fatigue life of 5760 cycles for a load range 1 to 10kN in the Y direction. These constraints represented a 10% relaxation on the fully welded condition. Initially a DOE study was conducted to obtain a feel of how the weighting factors influenced the resulting weld length. Once the DOE was completed, an optimisation using the Pointer algorithm was used. The design variables were the load case weighting factors. The response surface type for the Pointer algorithm was selected as unknown as this performs a basic Design of Experiments study at the start of the optimisation to indicate the direction in which the optimisation algorithm should move the weighting factors. Analysis outputs for design feasibility verification against optimisation constraints were the total weld length, minimum fatigue life and displacements at the loaded point. Weld and parent metal fatigue lives were calculated with the minimum of the two values being output to the optimiser.

Three optimisations were performed. One with the original weld / gap optimiser, one with the new seam weld optimiser and one with the laser weld optimiser. For the weld / gap optimiser, the design variables of weld length and gap length were allowed to range from 20-200mm. In the case of the seam weld optimiser, the minimum weld length was set to 20mm and the minimum gap length was also set to 20mm. The laser weld optimiser had a constant length of 20mm specified and a minimum gap length of 20mm.

6. Optimisation Results

6.1 “Regular Weld / gap” optimiser results

The weld / gap optimiser predicted a total weld length of 575mm compared with an original length of 1180mm. The resulting weld pattern is shown in Figure 6. It can be seen that there are two welds shorter than the intended minimum of 20mm and the number of welds is 30.

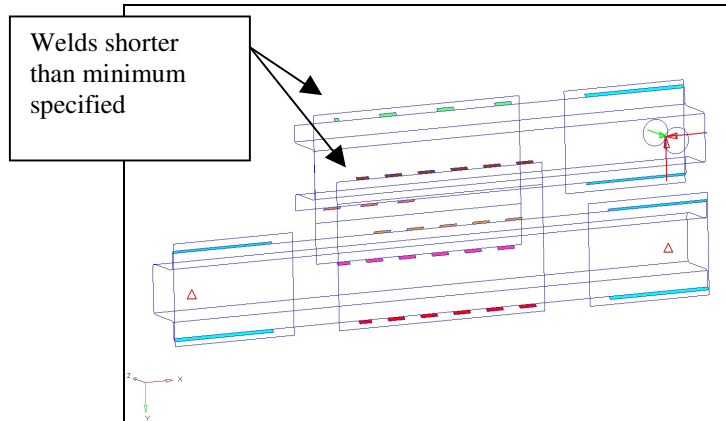


Figure 6. Optimised Weld Pattern from Weld / Gap Optimiser

6.2 Improved Seam weld optimiser results

The seam weld results predicted a total weld length of 565mm compared with an original weld length of 1180mm. The resulting weld pattern is shown in Figure 7 with only 10 welds in the optimised region shown in magenta.

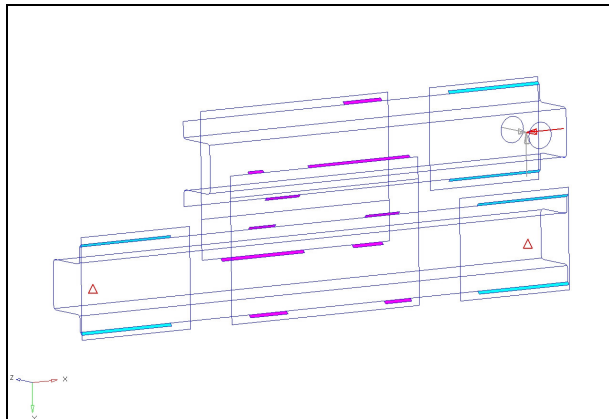


Figure 7. Seam Weld Optimised Pattern

6.3 Laser weld optimiser results

The laser weld results predicted a total weld length of 445mm compared with an original fully welded length of 1180mm. This was the shortest weld length of the three methods, but the number of welds was higher at 22. The resulting weld pattern is shown in Figure 8.

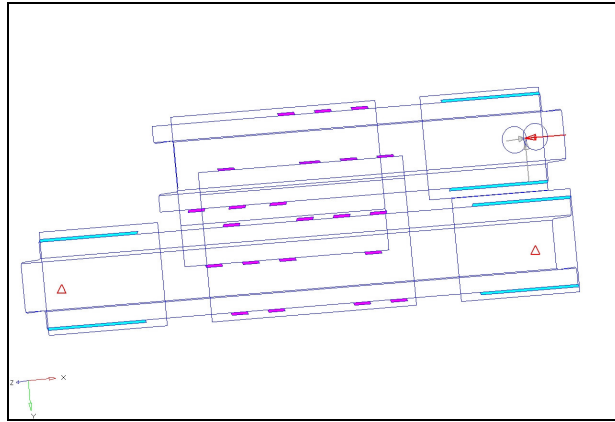


Figure 8. Laser Weld Optimised Pattern

7. Discussion

Results of the optimisations from all three methods are summarized in Table 2, together with the design constraint values actually achieved. As can be seen from the table, the laser weld optimiser produces the shortest overall weld length, but has the second highest number of welds.

Table 2. Results Summary

Weld Pattern Derivation	Weld Length	Number of welds	Fatigue Life	Deflection in Z
	mm		cycles	mm
Fully Welded Design	1180	6	6330	1.38
Targets			5760	1.50
Regular Weld/gap Optimiser	575	30	7127	1.49
New Seam Weld Optimiser	565	10	6291	1.49
Laser Weld Optimiser	445	22	6729	1.50

The new seam weld optimiser generates the lowest number of welds and produces a weld length slightly shorter than the original regular weld/gap optimiser. The difference in weld length would be greater if the short welds from the Regular Weld/Gap optimiser were lengthened to the required minimum length. The manufacturers that Tata Steel has collaborated with value minimising the number of welds in addition to the overall weld length.

The new seam and laser weld optimisers can be used with strain energy density input from Nastran or Abaqus. Alternatively, the optimisers can be used to translate the element density output from an Optistruct optimisation into a manufacturing feasible design for welding that meets the required fatigue performance.

A possible enhancement to the new seam weld optimiser would be to move welds to achieve the minimum gap rather than filling in the gap. This should result in a shorter overall weld length as seen from the laser weld optimiser, but could cause the number of welds to increase. The seam weld optimiser may be less efficient than the laser weld optimiser as it adds length both to short welds and to gaps that are too short. A further iteration could be added to the weld generation program after the short gaps have been filled in to determine if any of the welds can be shortened. For example, weld element 1965 in Table 1 could be removed as the weighted sum is below the threshold and the overall length of the weld exceeds the minimum length.

The laser weld optimiser currently works with a shell element representation of the welds meshed into the welded panels. Now that the weld pattern generation has been proven, the technique can be extended to include mesh-independent weld elements in solid or bar form.

During the development of the optimisers, several optimisation algorithms have been tried in Isight, but generally the Pointer method gives the best solution, provided that sufficient iterations have been performed. A typical number of iterations to be confident of an optimum design is 300-400, which can be accomplished overnight. The element size in the finite element model causes the overall weld length to increase in discrete steps. Hence, a small change in the weighting factors may cause no change to the total weld length or to the performance outputs. This will appear to show convergence to the optimiser, but a powerful technique such as the Pointer method can overcome this situation to find the true optimum solution.

8. Conclusions

The new seam weld optimiser only produces manufacturing feasible optimum solutions, so that the optimised weld pattern can be implemented directly into the vehicle design without

modification. The number of welds is minimised to limit the number of end-of-weld conditions, which improves the robustness of the design.

The Laser weld optimiser is an effective tool for optimising laser welds producing a feasible solution. It tends to produce shorter overall weld lengths than the new seam weld optimiser.

The laser weld capability can be easily adapted to accommodate mesh independent laser welds.

When optimising seam or laser welds, Tata Steel Automotive Engineering now has a suite of programs to deal with different situations. Isight is an effective software environment for engineers to customise and couple weld-line minimisation with steel thickness (gauge) optimisation, and carry out efficient multi-objective optimisations for automotive structural design and manufacturing.

9. References

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