Optimisation of Fixturing Clamps to Improve Panel Measurement Robustness

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Abstract

Tolerance measurement of sheet metal parts – such as those used in body in white assembly – is a critical task for the automotive industry that can lead to significant financial losses as a result of poor gauge R&R design and data misinterpretation. Current measurement systems use clamps to load panels onto fixtures. However, since non-rigid parts deflect with clamping pressure and under their own self-weight, measurement reproducibility and repeatability are affected by the number, location and sequence of the clamps.

This paper examines the suitability of LS-OPT® as a tool to determine an optimum clamping strategy for the measurement of a large bodyside panel. By minimising the number of clamps and limiting panel strain energy, a more robust and repeatable measurement is possible. After determining the optimum clamping strategy, a second round of optimisation was used to understand the sensitivity to clamping sequence.

To facilitate the large optimisation problem, LS-DYNA® implicit analysis was used to reduce computation time. The techniques adopted are discussed.

Introduction

As part of the manufacturing process Jaguar Land Rover regularly test the quality of pressed components by measuring them against CAD nominal. The intention is to identify any quality issues before they can disrupt the assembly line. For all pressed panels, but particularly larger components, care must be taken to hold the panel in a repeatable way so that accurate and robust measurements can be taken. To achieve this, Jaguar Land Rover design fixtures to hold the panels in place, and limit self-weight deflection, using a series of clamps. An example clamping fixture is shown in *Figure 1*.

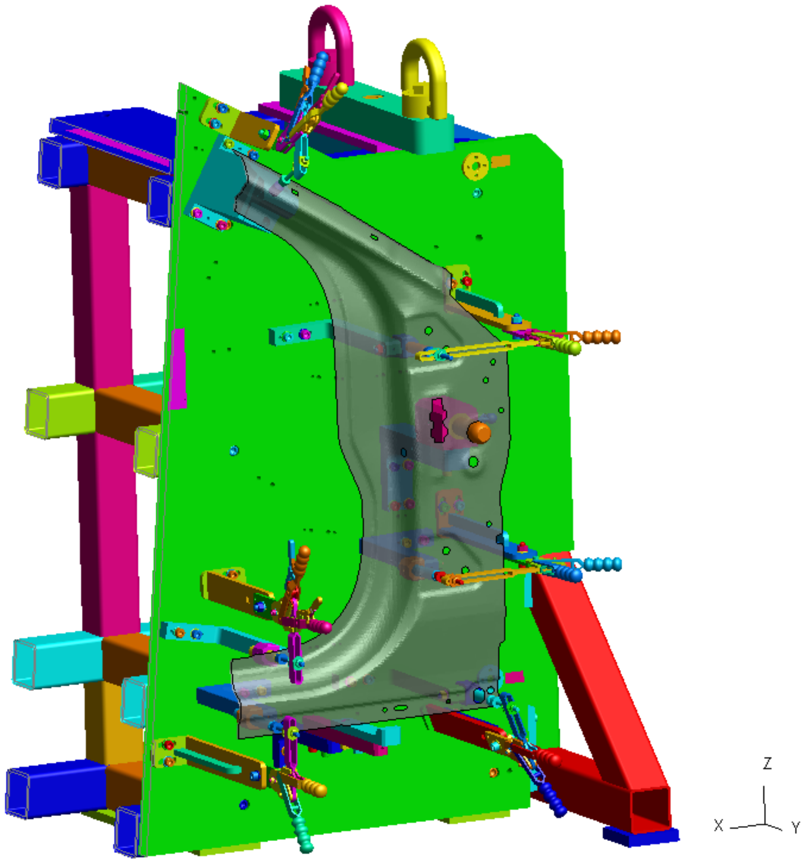

Figure 1 – Example clamping fixture

The difficulty with this method is that the fixture is designed to CAD nominal, thus the clamping causes the panels to be forced back to their nominal geometry. This potentially invalidates the measurements, and the more clamps that are used the less accurate the measurements are likely to become. As such, Jaguar Land Rover have raised the question: what is the minimum number of clamps required for a given part in order to repeatedly hold that part in its 'actual' dimensional state, and where should these clamps be positioned?

In collaboration with Jaguar Land Rover, Arup was commissioned to investigate the suitability of LS-DYNA and LS-OPT to model and optimise the clamping process. This paper outlines the approach taken by Arup to model the clamping process for a Jaguar Land Rover bodyside panel using LS-DYNA implicit, the optimisation studies performed using LS-OPT, and an overview of the findings.

Input Data & Preparation

Input data was required for the two main parts to be modelled in LS-DYNA; the panel and the fixture.

When building a CAE model, CAD is often used to derive an FE mesh that represents the physical part(s). However, as a non-nominal representation of the panel was required, Jaguar Land Rover supplied a bodyside panel FE model that had been generated by a LS-DYNA forming simulation. *Figure 2* shows the panel FE model and its deviation from CAD nominal. Springback and thinning effects were included as part of the forming simulation, but the effect of part internal stresses, part work hardening and also any effects due to clamp stiffness were omitted.

Although the supplied bodyside panel was provided in a LS-DYNA format, it contained an adaptive mesh due to the forming simulation. To keep the model as simple as possible, the adaptive mesh was removed by remeshing the panel (*Figure 3*). Relevant forming data, such as thinning, was remapped using Oasys PRIMER.

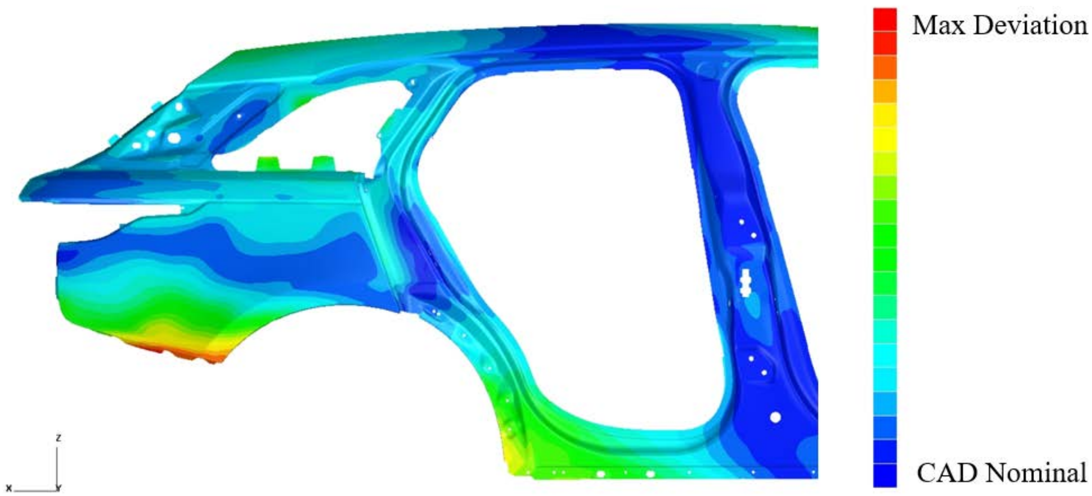

Figure 2 – Bodyside forming simulation data

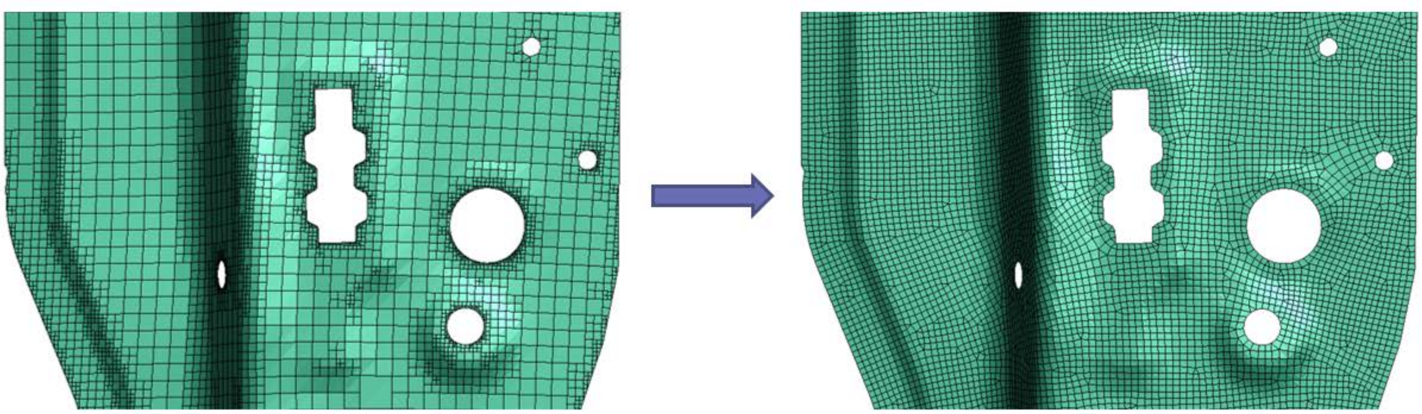

Figure 3 – Adaptive mesh removal

A representation of the fixture was also required in the LS-DYNA model. Rather than explicitly model the entire fixture, only the interface with the panel and relevant boundary condition definitions were required. To this end, the clamps were modelled using *ELEMENT_SHELL, with an additional *ELEMENT_DISCRETE connected via *CONSTRAINED_NODAL_RIGID_BODY used to represent the moving side of the clamp as shown in *Figure 4*. The material property for the discrete spring element was defined such that maximum force in the clamp was limited to the force specified by the clamping fixture. The local stiffness of the clamps was not captured in this study.

A note on terminology: each clamp has two sides. On the inside of the panel, the 'rest' is fixed to the clamping fixture. On the outside of the panel, the 'clamp' is moved via a hand-drawn mechanism (*Figure 4*).

The panel is located on the fixture (in reality and virtually) using two locating 'pins' (*Figure 5*). Combined, the pins ensure that the panel is seated on the fixture correctly and remove degrees of freedom such that the clamps are only required to push the panel back against the rests.

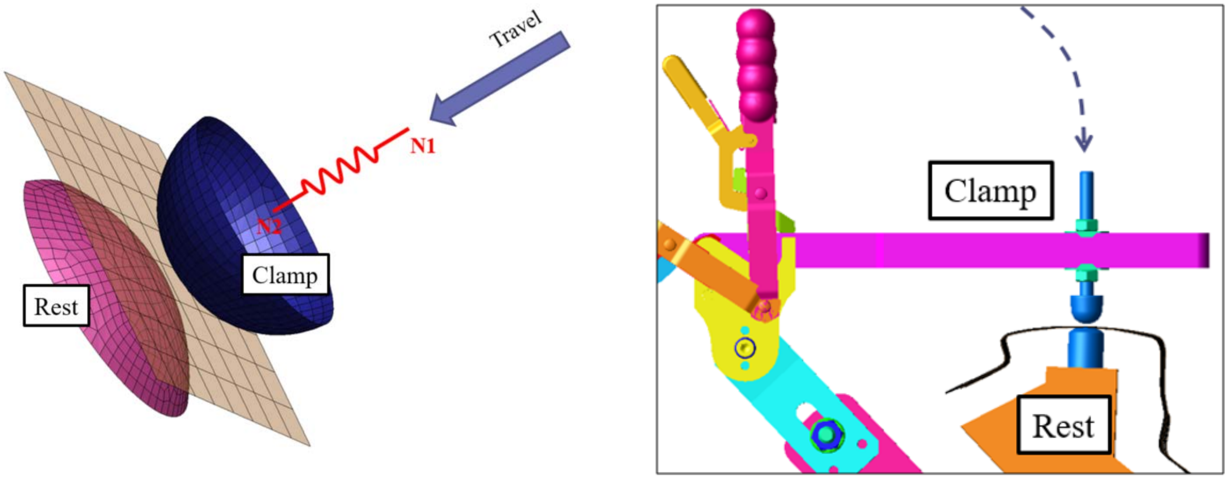

Figure 4 – Rest & clamp representation

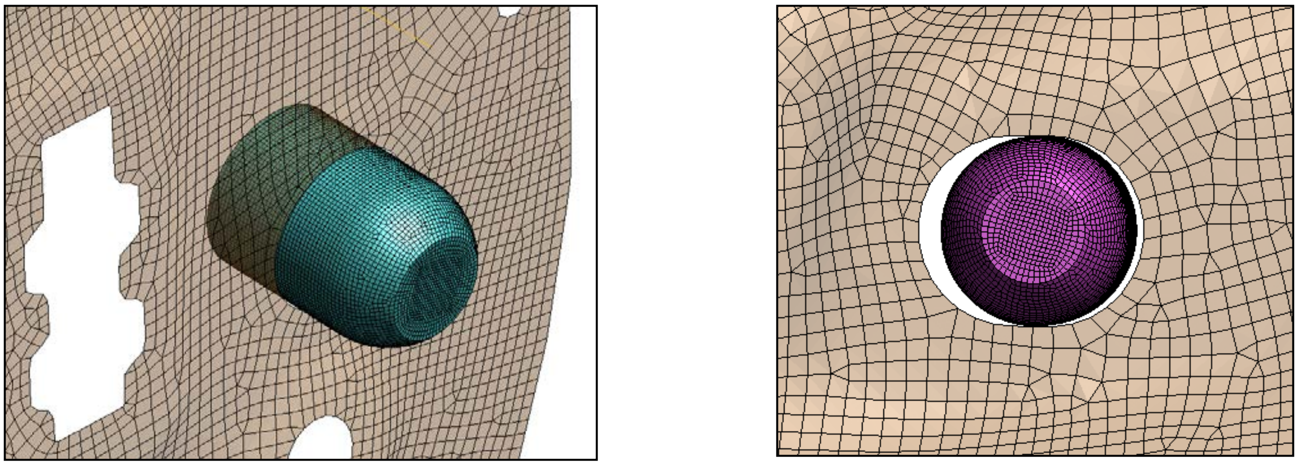

Figure 5 – Panel location strategy

Model Setup & LS-DYNA Implicit Sensitivities

Having prepared the input data, and meshed the fixture, the next stage was to setup the loading and boundary conditions to represent the clamping process.

In reality, the panel is manually loaded onto the fixture and allowed to settle on the positioning pins and rests, before the clamps are applied in a predetermined sequence. As it was not practical to model this process explicitly, the LS-DYNA analysis consisted of three distinct stages which cumulatively represented the real process as closely as possible.

Stage 1 – Gravity Ramp & Settling

The first stage of the LS-DYNA analysis represents the gravity loading and settling of the panel. Reproducing the process of translating the panel onto the pins and rests using LS-DYNA was deemed unnecessary and potentially difficult to achieve. Instead the panel was modelled in-situ, positioned as detailed earlier. However, as the panel was not of nominal geometry this posed the problem that the spatial relationship between panel and rests was unknown, and it was possible that a clash condition was introduced between the panel and some of the rests (*Figure 6*).

One of the most challenging aspect of this analysis was how to best handle clashes like these in a way that did not affect the validity of the results. It was decided that prior to the start of the LS-DYNA analysis, the clashing rests should be moved into a non-clash condition (*Figure 6*) and then moved back to their nominal position during the analysis (detailed later).

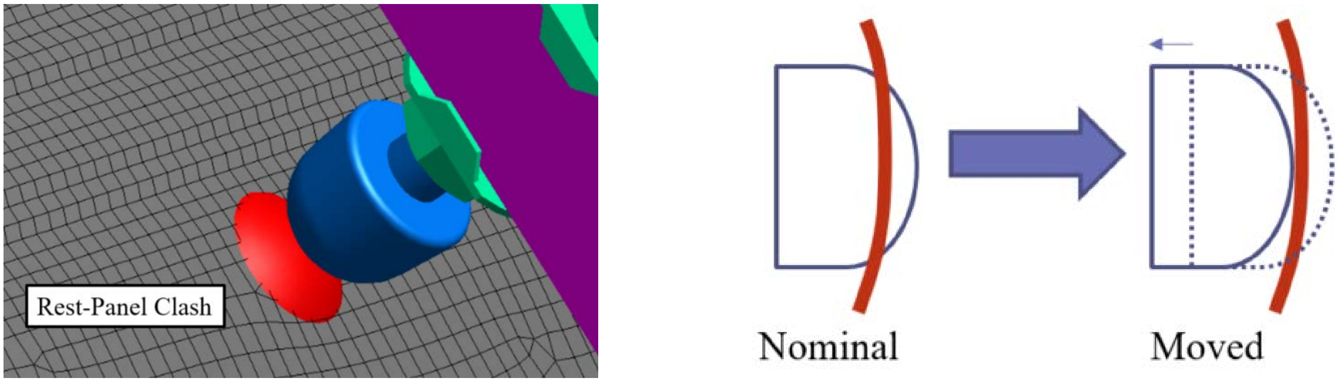

Figure 6 – Rest-panel clash

To ensure that the method was independent of panel geometry/forming data, all rests and clamps were positioned adjacent to the panel, regardless of whether they clashed initially. Contact between the panel and fixture was defined using *CONTACT_MORTER, which has been specifically developed for use with LS-DYNA implicit[1].

With the rests positioned to avoid a crossed-edge condition, gravity was ramped up from zero over the first five states of the analysis. Allowing the panel to settle under gravity supported by out-of-position rests could give rise to a potential error state in comparison to the real settling behaviour, however because the gravity loads and deflections were low relative to those generated by the clamping, this was deemed to be acceptable. Note: during the settling the rests were fixed in space using a zeroed *BOUNDARY_PRESCRIBED_MOTION.

One problem with this approach was that it required careful positioning of many components, which would have been time consuming if done manually. To avoid this, a script was written that utilised the JavaScript API provided by Oasys PRIMER to automate the positioning process.

A second problem was that by having both sides of the panel in contact there was an increased risk of unrealistically constraining the settling behaviour. This was overcome by defining the clamping spring material such that very low forces developed at small displacements, thus any clamp forces were small compared to gravity (*Figure 7*).

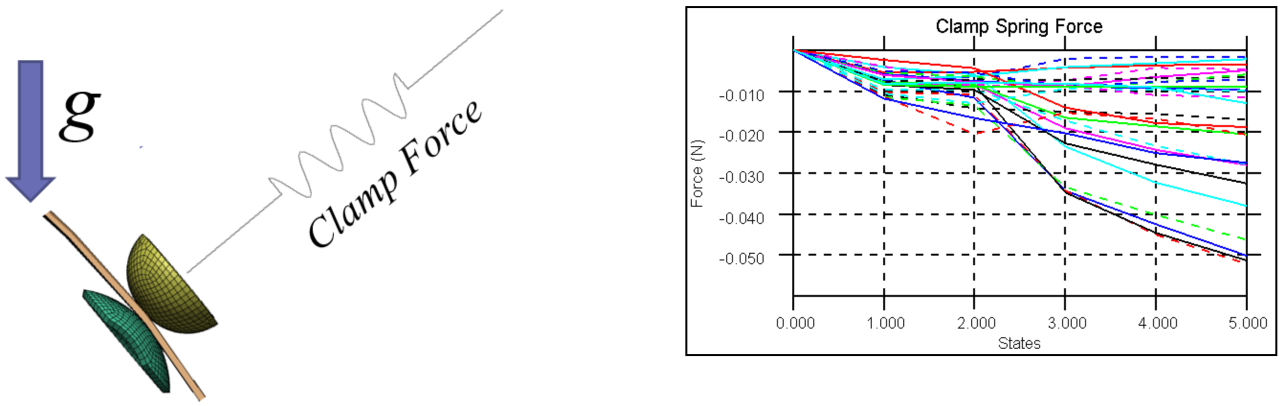

Figure 7 – Clamp & low clamp load during gravity ramp

Stage 2 – Clamping

Once settled, the physical panel is held in place by manually applying the clamps in sequence. In LS-DYNA both the application of the clamps and the movement of the rests back to their nominal positions must be represented. It was found that if the rests were moved prior to the clamps being fully applied the resulting panel displacement could cause convergence problems. Consequently, the second stage of the LS-DYNA analysis was the application of the clamping force.

The force application was achieved using *BOUNDARY_PRESCRIBED MOTION applied to the free end of the clamp spring. The *BPM was such that motion normal to the clamp axis was not permitted. The nodal rigid body used to connect the clamp spring and mesh was constrained so that it too could only move along the clamp axis.

The material model used for the springs was defined so that at low displacements very little force was developed (as required during Stage 1) and at higher displacements the force was limited, as determined by the clamping fixture. A positive side effect of the force limit was that the springs could be displaced far more than necessary without introducing excessive load – making it possible to ensure that all springs had the required level of force independent of the panel starting position or how it displaced during the analysis.

To reduce run time and improve LS-OPT throughput, the clamping sequence was not represented at this stage. Instead all clamps were applied simultaneously. *Figure 8* shows the clamp loads over the first 10 states.

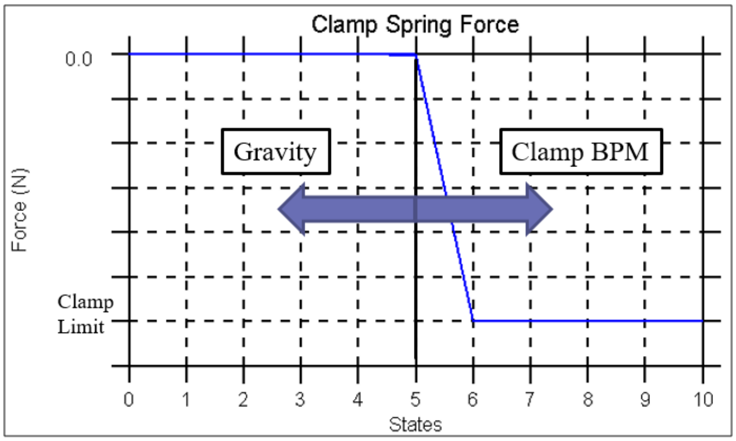

Figure 8 – Clamp spring force | Stage 1 & 2

Stage 3 – Rest Repositioning

During the final stage of the analysis the rests were moved back to their nominal positions. This represented the most significant panel loading and is analogous to when the physical clamps are applied. The movements are driven via *BOUNDARY_PRESCRIBED_MOTION, which up until this point had been set to zero.

Like the clamping in Stage 2, during this stage all rests were moved at the same time, however each rest moved at its own individual rate taking 5 solution states to achieve its final position. Some rests moved to oppose and compress the clamping springs, while others moved with the springs causing them to elongate. However, as all of the clamping springs had been compressed more than necessary a constant clamping force was maintained throughout (*Figure 9*).

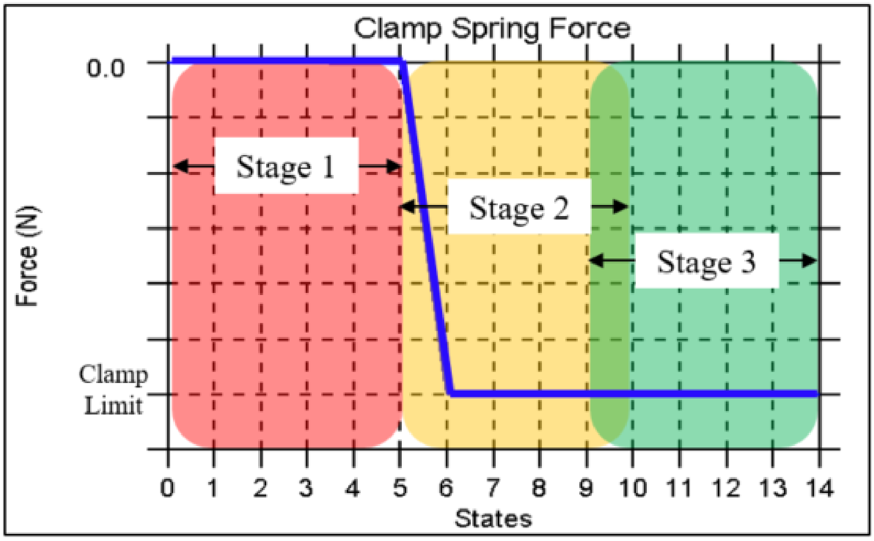

Figure 9 – Clamp spring force | All stages

Figure 10 shows the internal energy for the panel, highlighting the significance of Stage 3 in terms of deformation. The energy/deformation during Stage 2 was comparatively low, because during this stage the clamping force was predominantly closing any small panel to rest gaps, introduced by gravity during Stage 1.

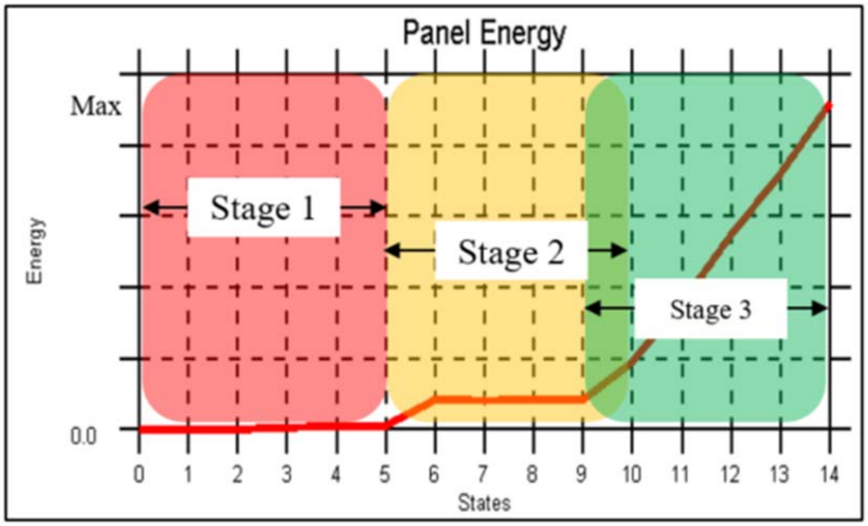

Figure 10 – Panel internal energy | All stages

Additional LS-DYNA Implicit Settings

Setting up a LS-DYNA analysis to successfully run using the implicit solver can require more attention to detail than a comparable explicit analysis. One difference to note is the choice of element formulation; for the clamping analysis element formulation type -16 was used in favour of the usual type 16, as it has been modified for higher accuracy – a must for implicit analyses.
Additional *CONTROL cards were also set to improve accuracy and robustness. The implicit solution method used was NSOLVR = 12 – *Experimental non-linear with BFGS updates + optional arclength.*

LS-OPT Definition

Once a robust and error free model had been achieved the next step was to prepare LS-OPT. The first stage of any optimisation is to consider what input parameters there are; and in the case of the clamping optimisation the input parameters were the clamps (and corresponding rests) themselves, and whether they were present or not. To this end, a *PARAMETER definitions were created to represent each of the clamp/rest pairs, taking the value of 1 when active in the model, and 0 when inactive.

Several options were considered for how to make the clamps inactive during the analysis, including part deletion, moving the parts away from the panel, supressing the *BPM definitions and preventing contact with the panel. It was decided that the most elegant way to deactivate the clamps was to take them out of contact with the panel so they could not exert any force. A simple way to do this would have been to create individual *CONTACT definitions for each of the clamp/rest pairs and set an appropriate birth time. However, in practice it was found that this approach resulted in longer run times which would have limited the size of optimisation.

Alternatively, a single *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR contact was used between the panel and a *SET_PART containing all of the active rests and clamps. Whether clamps/rests were included in the *SET_PART was ultimately determined by the clamp/rest pair *PARAMETER value, implemented via a complex system of *PARAMETER_EXPRESSION definitions and intermediate *SET_PART cards.

With the model parameterised, LS-OPT could be programmed as shown in *Figure 11*.

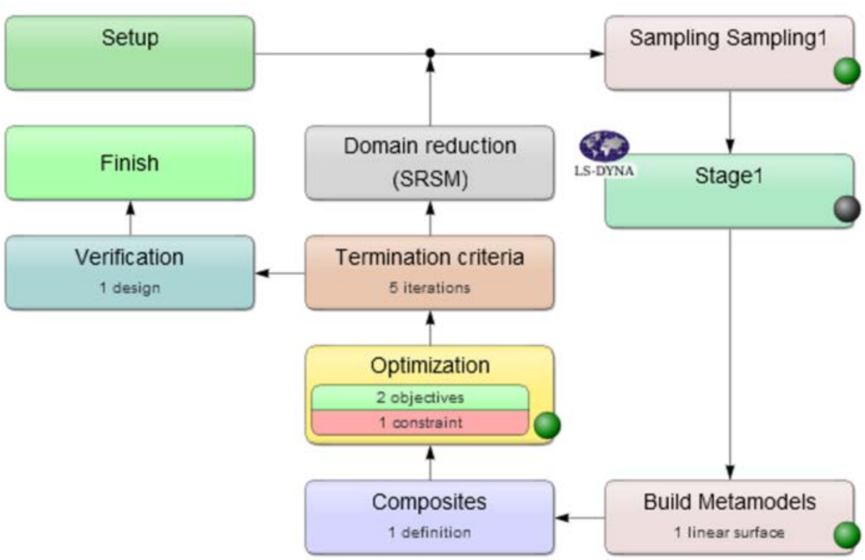

Figure 11 – LS-OPT setup

Due to a finite amount of CPU resource, a simple linear polynomial meta-model with additional iterations was adopted over a more complex model with fewer iterations. Default D-Optimal point selection was used, as was SRSM domain reduction.

The optimisation was given two objectives: reduce internal energy and reduce clamp count. The only constraint applied was for a sensible minimum number of clamps, to prevent error terminations due to unrealistic clamping strategies.

Initial Result

The optimisation ran successfully generating several hundred data points. *Figure 12* shows the solution space for the two objectives.

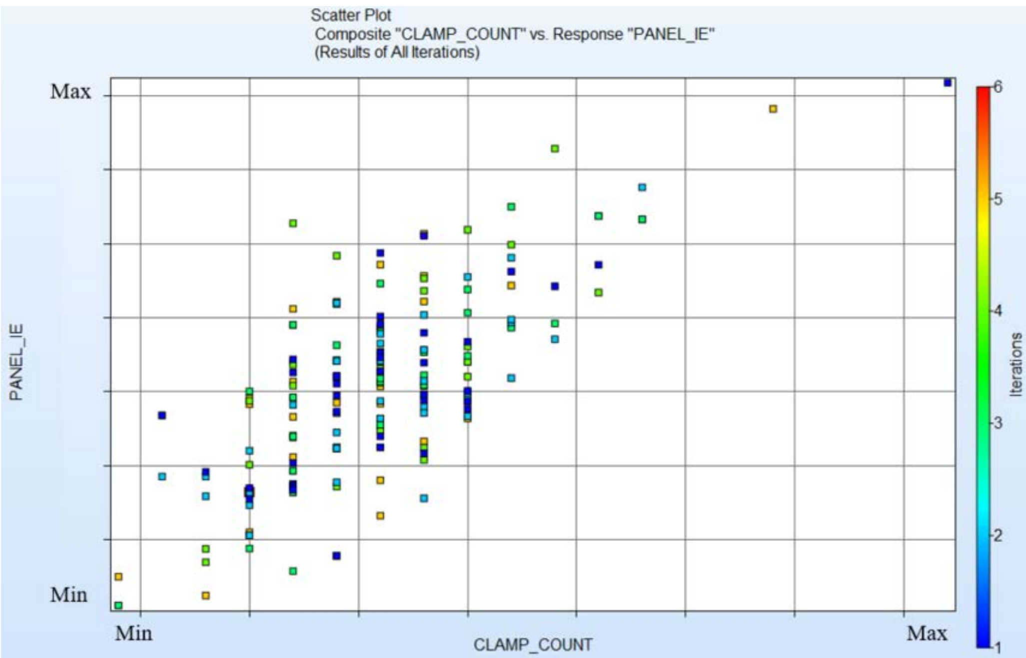

Figure 12 – Study 1 solution space

Although the optimisation ran successfully for five iterations it did not show signs of convergence. The amount of scatter present in iterations four and five was found to be comparable to one and two. This is likely due to the binary nature of the input parameters not being best suited for LS-OPT, which works best with continuous parameter definitions. Nonetheless, LS-OPT did provide a well-balanced representation of the solution space.

Figure 12 shows a clear relationship between panel internal energy and number of clamps. At the time of running the optimisation it was unclear whether deformation due to gravity would be most significant at low clamp numbers, creating a bi-linear ‘hockey stick’ type of relationship which could then be used to identify the ‘optimum’ clamping strategy (*Figure 13*).

Unfortunately, rather than a well-defined bi-linear relationship the results suggested a linear relationship between clamp count and panel internal energy. This made it difficult to select a clamping strategy based on internal energy alone as the data would suggest zero clamps are optimum, which is not feasible.

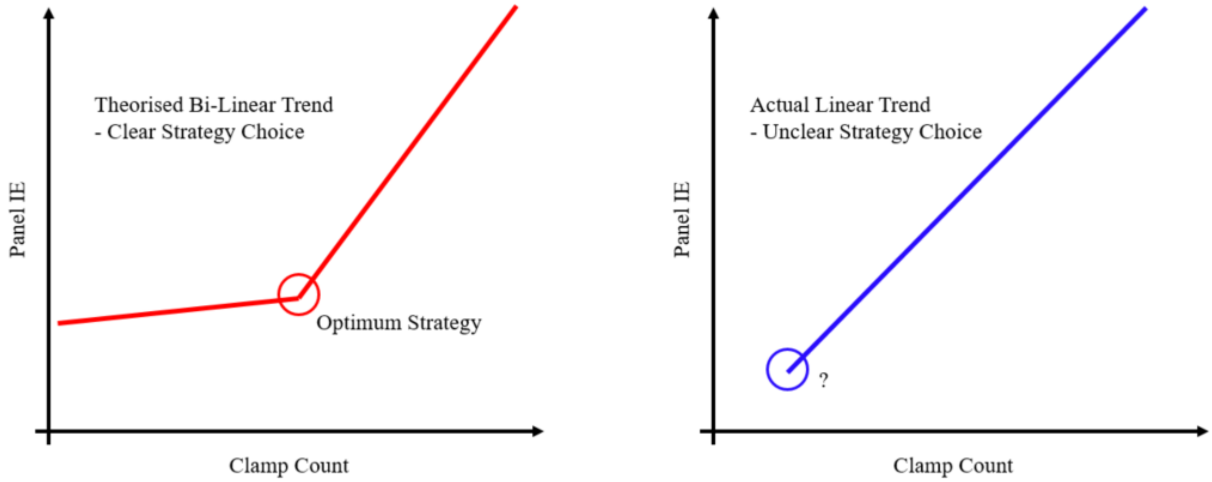

Figure 13 – Energy trendlines

Additional Data Mining

To progress the study further additional data was required. Having one data point per strategy (panel internal energy) was insufficient; a per clamp metric was needed. As the clamping force was ultimately driving the majority of panel deformation, it was sensible to extract the force at each individual clamp. However, as the clamp springs were force limited, they could not be used. Instead, the boundary forces at each rest were extracted.

To do this retrospectively via LS-OPT would have been very difficult. Instead a custom JavaScript was written for Oasys T-HIS to extract and collate the rest forces, for all of the analyses. This data was then fed back into LS-OPT, along with the maximum rest force recorded for each analysis.

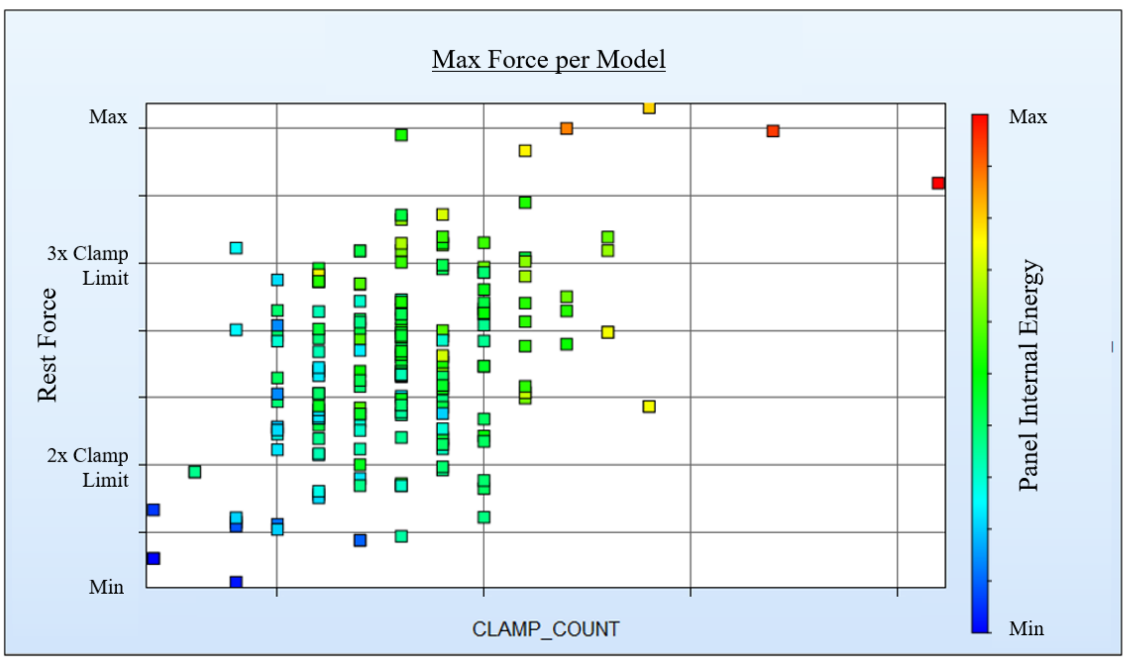

Figure 14 – Maximum rest force versus clamp count

Figure 14 is useful because, although the trend is less clear, it illustrates that for a given clamp count there is a large range of maximum forces, and that the maximum force at the rests can be several times that applied by the opposing clamp spring.

Although the net force on the panel/rests is equal to the sum of the applied clamp forces, the geometry of the imperfect panel means that the distribution of load varies (*Figure 15*):

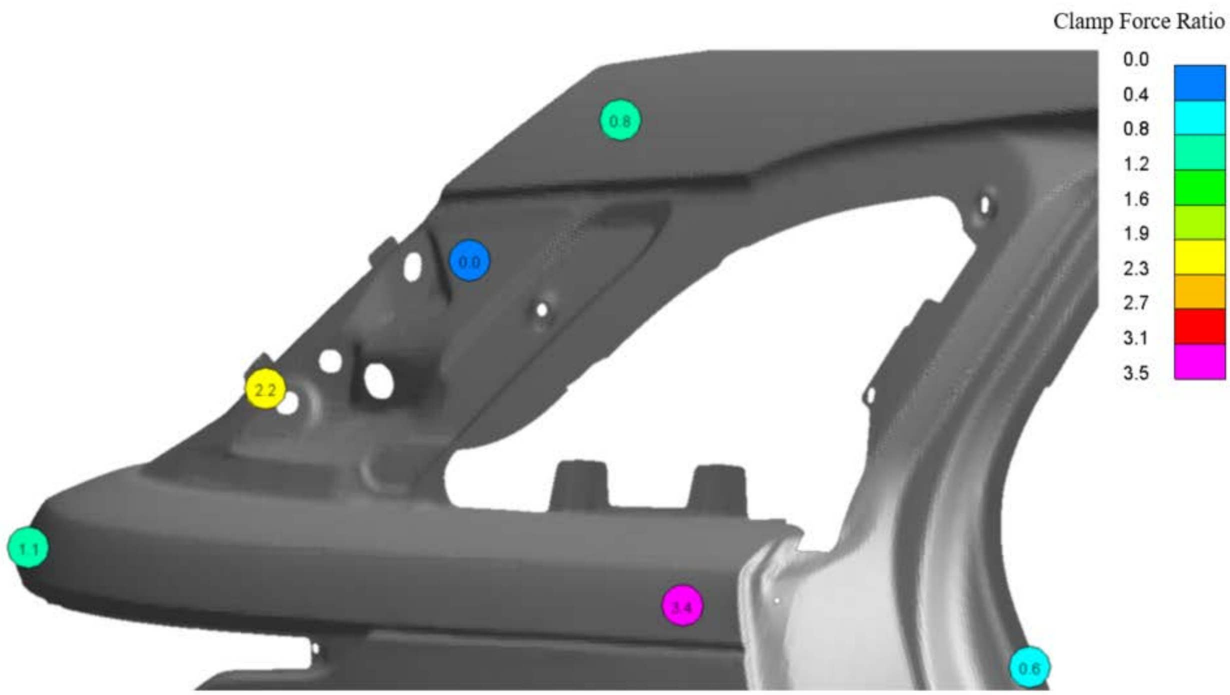

Figure 15 – Clamp force (ratio to clamp limit)

From the chart shown in *Figure 14* and plots like *Figure 15*, it was possible to start identifying trends in clamping strategies. For example, the data suggested that 'good' strategies have multiple A and B-post clamps, and that clamping near quarter glass is likely to result in high forces. LS-OPT's correlation matrix is also useful for identifying clamps which contribute most strongly to internal energy (*Figure 16*):

				PANEL_IE			
Clamp 1	0.06	-0.00	0.02	0.07	0.47	0.07	0.03
Clamp 2	0.06	0.06	-0.07	0.09	0.18	-0.01	0.05
Clamp 3	-0.10	-0.02	0.00	0.38	0.02	-0.16	-0.03
Clamp 4	-0.03	0.04	0.04	0.11	0.03	-0.01	0.08
Clamp 5	0.01	-0.04	0.03	0.21	-0.09	-0.08	0.03

Figure 16 – LS-OPT matrix of correlation factors | Clamp 3 shows strongest link to panel IE

Clamp Ranking Metric

The data generated by considering clamp forces in addition to panel internal energy is useful when comparing the different strategies and isolating clamps/rests that generate excessive force. However, the data in its current form still does not lend itself to being able to select a single 'optimum' clamping strategy. To help resolve this issue a method for ranking the clamps based on the rest forces was developed.

For each analysis, the clamps were ranked based on the force experienced by the rest, and a score was allocated; the clamp experiencing the lowest force scored 1 point, and the Nth ranked clamp scored N points. Average scores were calculated based on the number of analyses that each clamp was active in. These average scores were then ranked so that over the solution space it is possible to identify which clamps experience the lowest forces. A simple illustration of the system is given in *Table 1*.

	Forces/Points			
	Clamp 1	Clamp 2	Clamp 3	Clamp 4
Strategy 1	1	2	3	N/A
Strategy 2	1	N/A	3	2
Strategy 3	2	1	N/A	3
Strategy 4	1	3	4	2
Point Sum	5	6	10	7
Average	1.25	2	3.3	2.3
Rank	**1**	**2**	**4**	**3**

Table 1 – Example clamp ranking

Although the average clamp force will always be equal to the load applied by the clamp springs, when ranking:

- Low forces (rest force < clamp limit) are desirable because they represent points on the panel that can be deformed to meet the nominal CAD position by a relatively low load. During assembly this level of panel manipulation is acceptable and hence if the measurement captures this, it too would be acceptable.

- Zero force indicates that the panel is not touching the rest i.e.: the panel cannot achieve its nominal shape under the clamping load. This is an error state. Any measurement which detects this condition is fulfilling its purpose therefore it is acceptable for a clamp strategy to result in a zero rest force condition.

- Clamp forces roughly equal to the clamp load are acceptable because they are indicative of a nominal geometry and the rest is simply reacting the clamp force with little panel contribution.

- Forces much greater than the clamp limit represent areas of the panel which are far from nominal and are being forced into shape via the clamps. This is to be avoided as it results in an acceptable measurement but a problem during assembly where the high force cannot be achieved. Rest forces > clamp limit may also be introduced via load transfer from low force regions, this situation would be acceptable and would manifest itself as a clamping strategy with some high force but with lower panel energies than those where the high force is due to the panel geometry.

Given the above, the clamp rank table can be used to select the ‘best’ N clamps for an N-clamp strategy. To test whether this would work in practice, a model was analysed using a selection of top ranked clamps. *Figure 17* shows the maximum force and internal energy solution space with the test model highlighted.

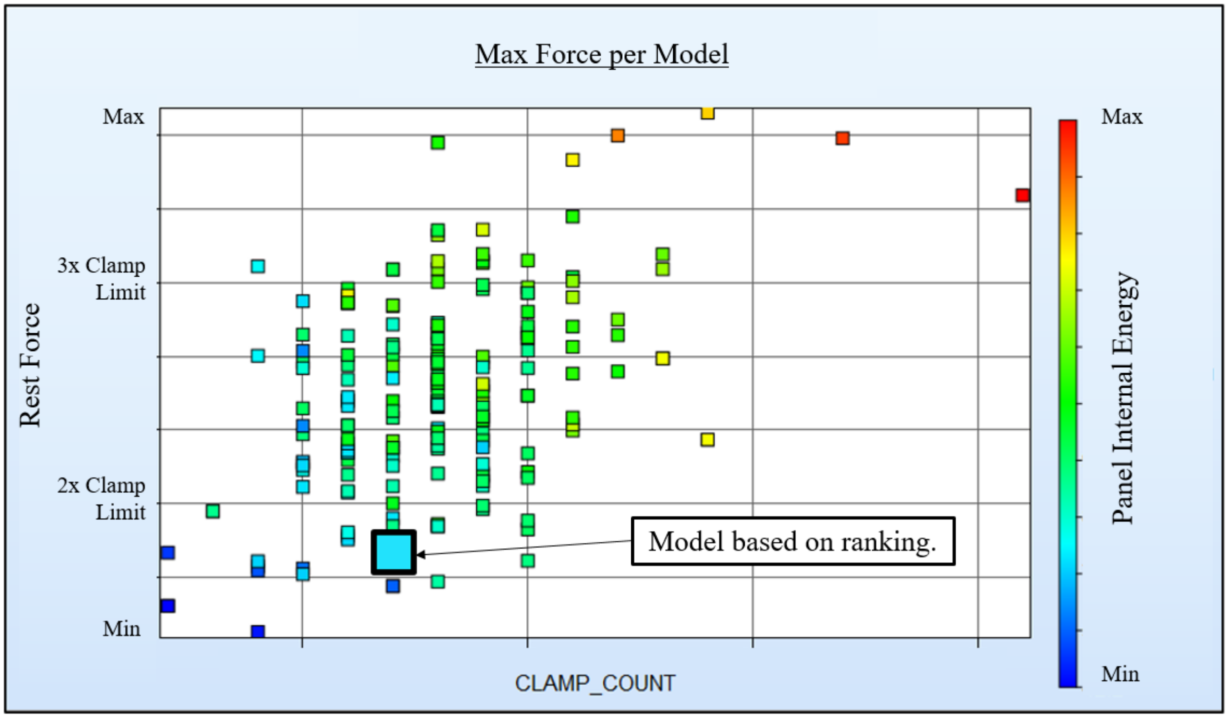

Figure 17 – Solution space showing strategy determined by clamp ranking

It can be seen that the ranking method was able to identify an N clamp strategy very close to the ‘optimum’ as found via LS-OPT. This gives confidence that the ranking methodology works and could be used as a design tool given a reasonable solution space.

Sequence Study Setup

Having successfully identified a method for objectively selecting where to best locate N clamps, the second stage of the study was to determine whether there is an optimum sequence in which to apply the clamps.

The LS-DYNA model in the first study had the clamps applied (and rest moved back to nominal) at the same time. In the second study the model was modified such that the time at which each rest was moved was unique and determined by a LS-OPT input parameter.

The base model for this study was the test model used to verify the clamp ranking methodology, with no other changes. Clamp spring forces were applied simultaneously across the panel after gravity, only the rest movement is unique. As with the first study, a simple linear polynomial model with D-optimal sampling was used, this time with three iterations. No constraints were applied and the objective was still to reduce panel internal energy (*Figure 18*).

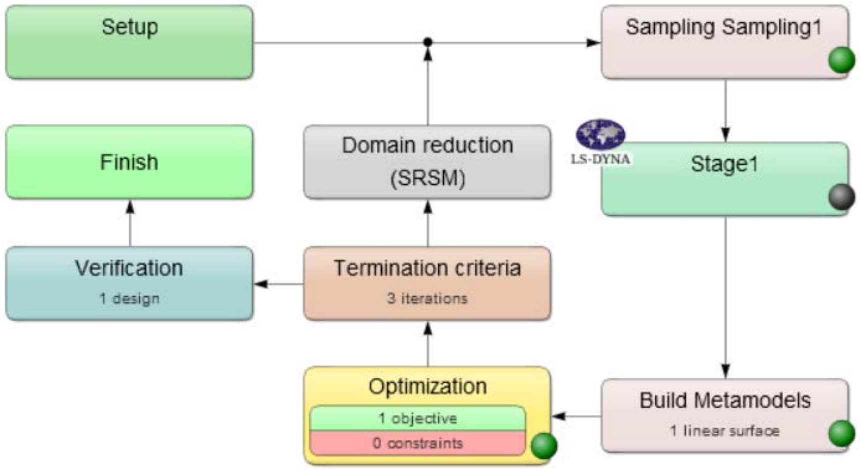

Figure 18 – Sequence study LS-OPT setup

Sequence Study Result

It is clear from *Figure 19* that during the optimisation process LS-OPT has been able to reduce the internal energy by tuning the order in which the clamps are applied. In the process, maximum forces have also reduced as shown by *Figure 20*. Although the differences are relatively humble, as shown in *Figure 21*, they are real and measurable.

This study demonstrates that given a reliable model LS-OPT is capable of determining the optimum clamping sequence. This method could be applied to existing components and fixtures to generate improvements at no cost associated with additional equipment or modifications.

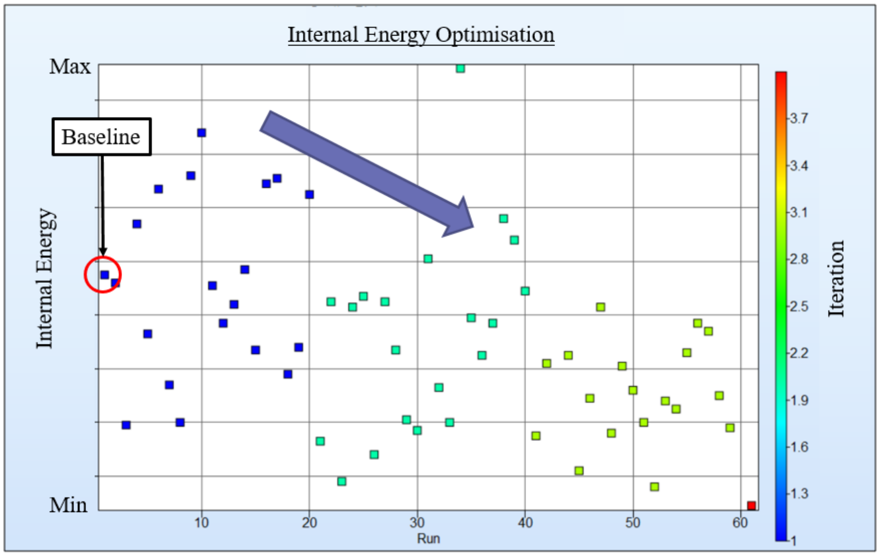

Figure 19 – Sequence study IE solution space

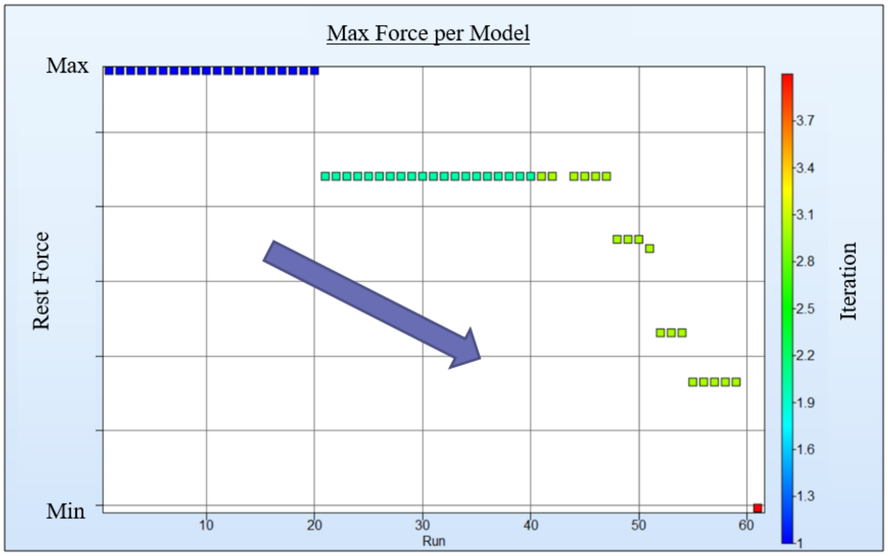

Figure 20 – Sequence study maximum force solution space

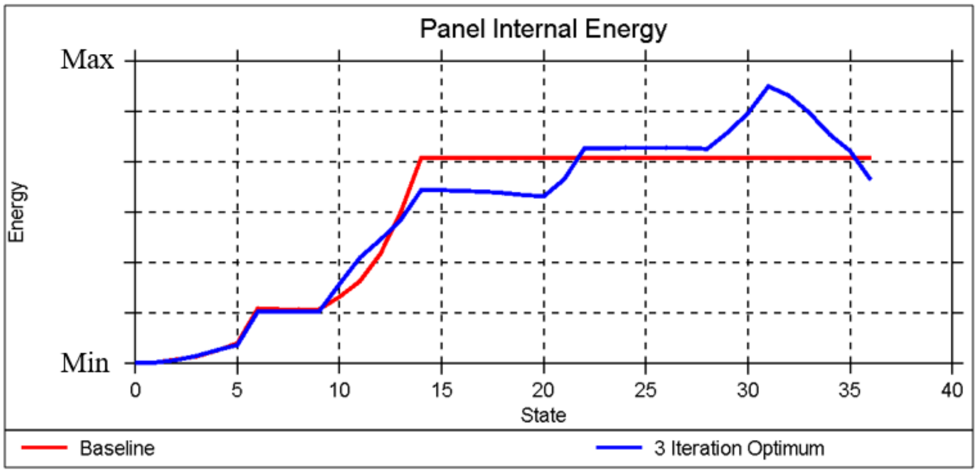

Figure 21 – Panel internal energy for optimum sequence

Summary

This study has explored the use of LS-DYNA and LS-OPT as design tools for improving clamping fixtures to provide more reliable measurements. The clamping process was successfully modelled using LS-DYNA implicit, which resulted in run times short enough to make large scale optimisations possible.

It was initially hoped that LS-OPT would be able to identify the optimum number of clamps, however in practice this proved difficult to achieve; partly due to the objectives/constraints applied to LS-OPT and partly due to the nature of the problem. Alternatively, a methodology for ranking the clamps was developed and, after some additional data mining, the LS-OPT solution space was used to successfully rank the various clamp locations based on the force they generate. This ranking was shown to work well; producing a result close to the 'optimum' as found via LS-OPT.

A second study was also included in which the clamping sequence was optimised. The results of this showed very clearly that, given an accurate model, LS-OPT could be used to optimise the sequence by which the clamps are applied, to achieve lower forces and panel internal energies. This method could be deployed on existing fixtures to generate improvements at no added cost associated with additional equipment or modifications.

Further Work

This study was designed to be a proof of concept as to whether CAE techniques could be applied to one the challenges faced by Jaguar Land Rover manufacturing. Going forwards, this work forms a base for future studies to further explore the sensitivities of the problem. Such future studies may include:

- Sensitivity to clamp force limit.
- Sensitivity to clamp friction.
- Sensitivity to clamp shape/form.
- Improved forming analysis.
- Repeating the study for other panels and geometries.
- Additional physical testing to verify clamp strategy improvement predictions.

Additional investigations could also consist of: capturing the local stiffness of the clamps, and the effect of including panel work hardening including internal stresses. These were omitted for this initial study but may influence the behaviour of the panel during clamping.

Once enough work and validation has been undertaken a formal design process may then be introduced and adopted for new vehicle programmes.

References

[1] Livermore Software Technology Corporation (LSTC), LS-DYNA Keyword User's Manual, Volume I, 2016.