Application of Design of Experiments in Crash beam development

Ahmed Oshinibosi
ThyssenKrupp Tallent Limited

Contents

Company Introduction ~ Thyssenkrupp Tallent

Capability

Design

Simulation

Testing

Prototyping

Locations

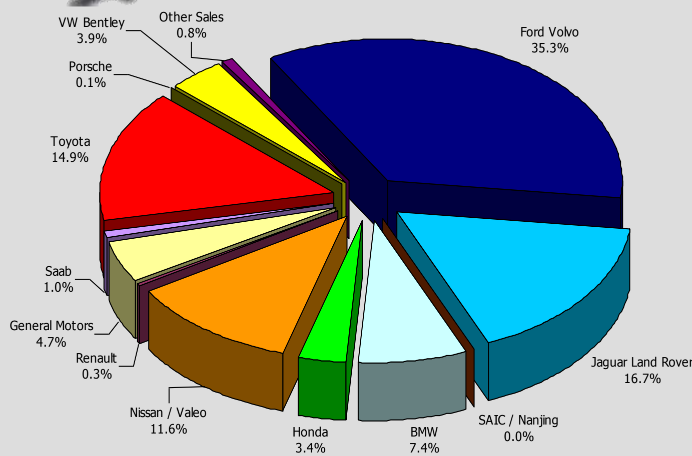
① **Bourn**
(ThyssenKrupp AutomotiveTallent Chassis)
- Chassis Pressings and Assembly plant

② **Cannock**
(ThyssenKrupp Body Stampings HQ)
- Body Pressings and Assembly plant

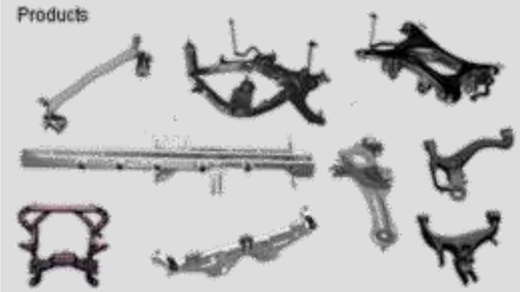
③ **Fareham**
(ThyssenKrupp Body Stampings)
- Just-in-time manufacturing facility

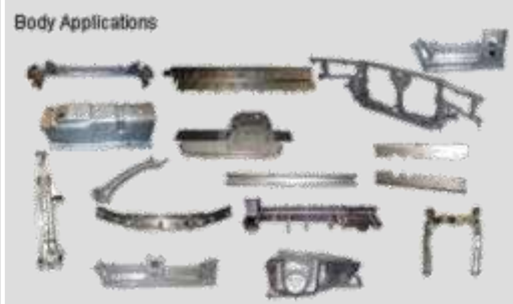
④ **Llanelli**
(ThyssenKrupp Camford Pressings)
- Body Pressings and Assembly plant

⑤ **Newton Aycliffe**
(ThyssenKrupp AutomotiveTallent Chassis HQ)
- Chassis Pressings and Assembly plant



Products





ThyssenKrupp

The Design Challenge

- This investigation was carried out to assess the improvements obtained using DOE and to study the effect of crush-can geometries on the performance of the crash beam shown in Fig 1a. This performance is measured in terms of section-force vs time.
- The beam is set up to crash into a Thatcham offset rigid barrier with an Inertia of 1000kg to account for the mass of the missing vehicle parts and a traslational velocity of 10mph (4.44m/s) in x-direction.
- The resulting performance is shown in Fig 1b.
- It was then required that the Section-force of the baseline results be improved especially between 0.0 and 0.03s of the time interval.
- A smoother response is also required to fall between 85kN and 106kN (shown in black).

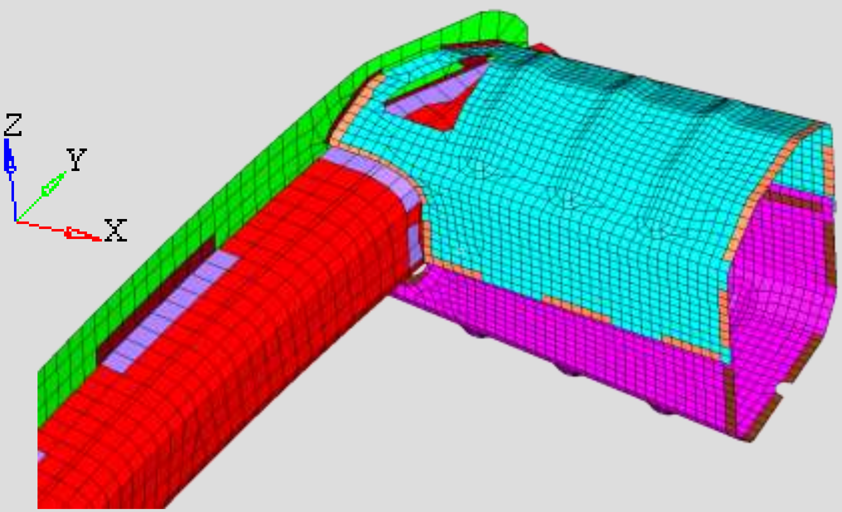


Fig 1a: Crash beam to be investigated

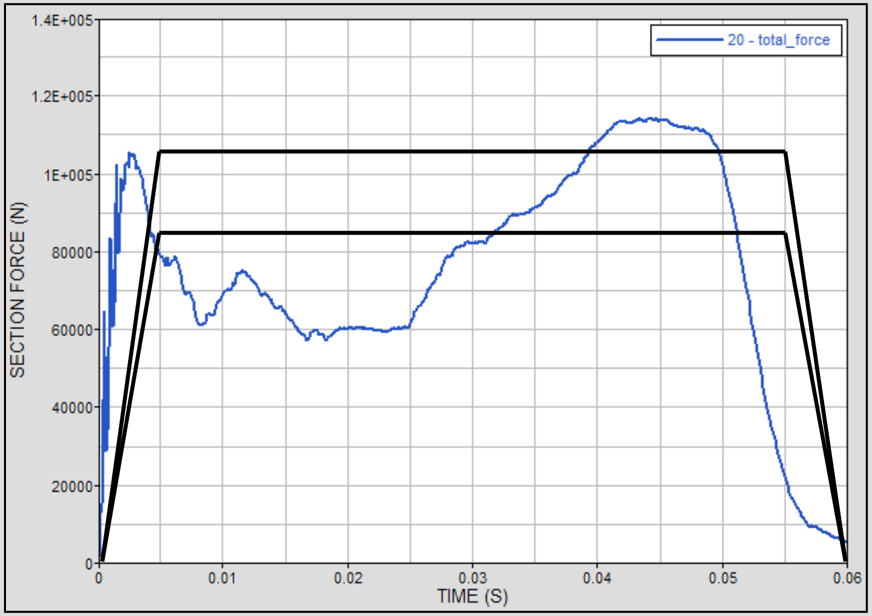


Fig 1b: Current performance

Design of Experiment

- Objective: The objective of this DOE study is to understand how the crush can geometries influence the crash performance of the whole beam and to see which combination of forming geometries gave the highest section force. It is also desired to produce a design which would give a constant response over the time interval.

- Model parameters: These are the different shapes created from morphing the Swages on the Crush cans highlighted in fig 1c and 1d. Swage heights, distance between successive Swages and the size of holes highlighted below are morphed to create 21 shape variables.

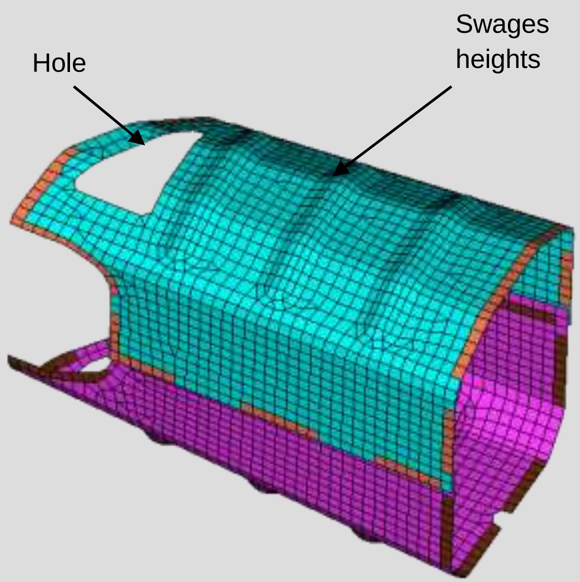


Fig 1c: Top of Can

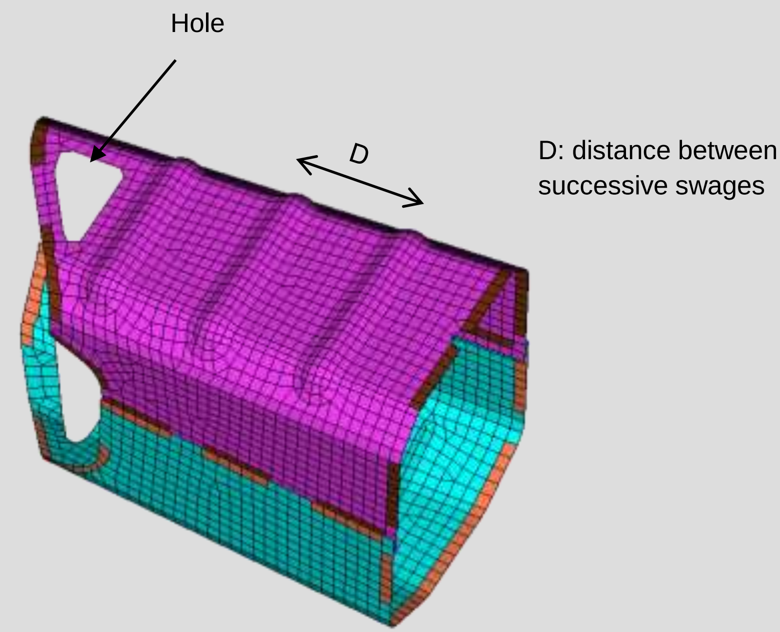


Fig 1c: Bottom of Can

Design of Experiment

By launching Hyperstudy from inside Hypermesh, the shapes generated from the morphing process are automatically recognised as potential variables. It also allows the shapes to be easily selected and assigned lower and upper bounds when adding modal parameters as shown.

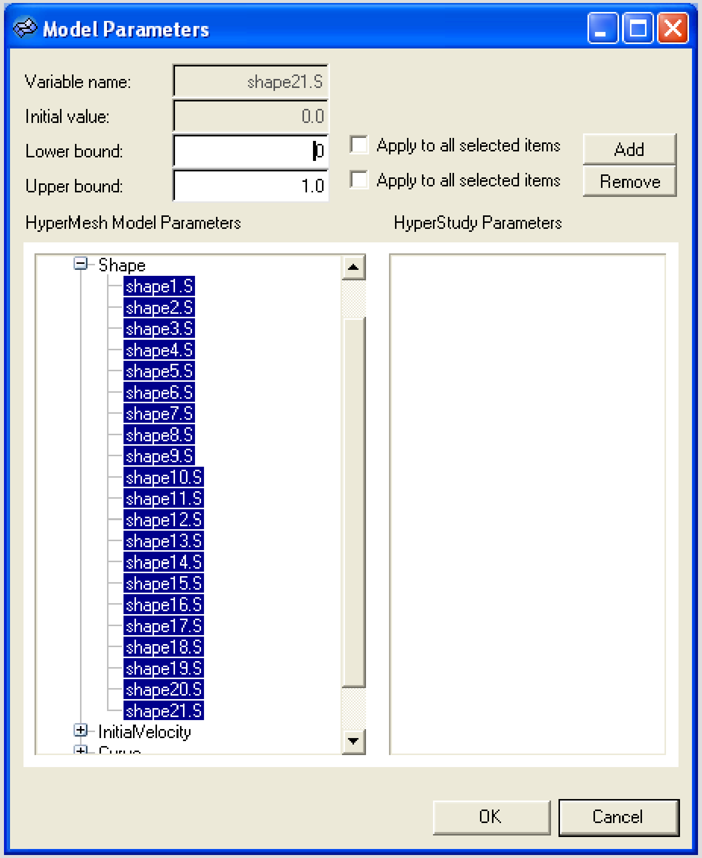
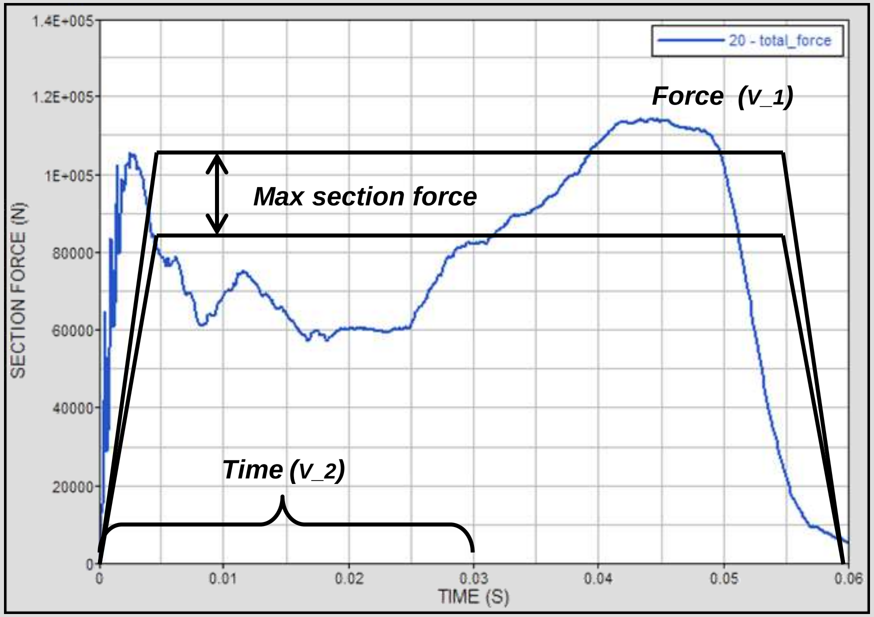


Fig 1e: Variable set-up

Design of Experiment

- <u>Responses set-up</u>



Four responses were defined : (1) Maximum section force, F = max(v_1)

(2) Energy, T_t = lininterp ({v_2},{integral(v_2,v_1)},t), for t = 0.01s

(3) Energy, ,, ,, ,, , ,, t = 0.02s

(4) Energy, ,, ,, ,, , ,, t = 0.03s

The linear interpolation function estimates the Section force for each time (t) such that the new points lie on or near the Maximum section force of the initial performance.

Design of Experiment

In this scenario, 128 runs were executed and written by Hyperstudy. The equation below explains how Hyperstudy DOE combined the various parameters

$$Y_n = m_1S_1 + m_2S_2 + m_3S_3 \ldots\ldots\ldots\ldots\ldots + m_nS_n \qquad \text{where } c_1 < m_n < c_2$$

Y_n = nth run

S_n = nth shape

m_n = multiplier

c_1 and c_2 are the Lower & Upper bounds of the multiplier respectively

n = number of runs

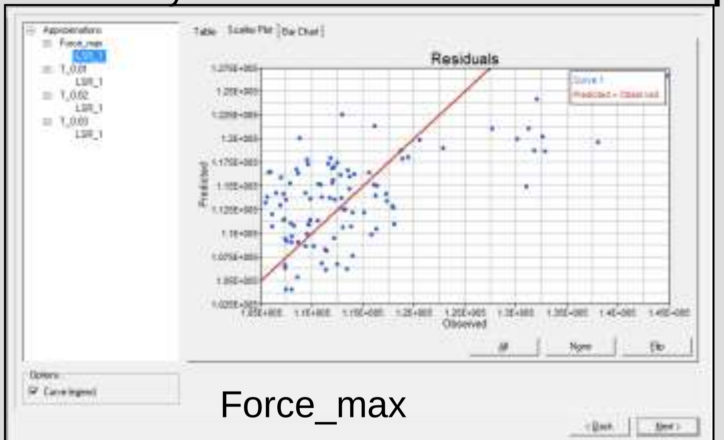
$$Y_1 = 0.01S_1 + 0S_2 + (-0.133)S_3 \ldots\ldots\ldots\ldots\ldots$$

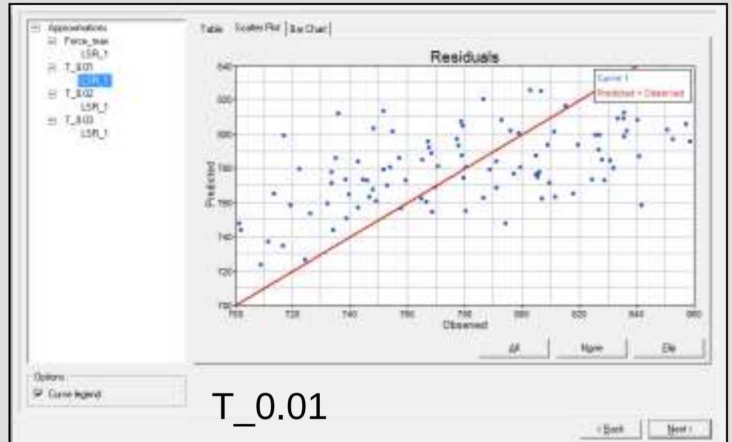
DOE Run Table | DOE Run Plot | DOE Run 3D Plot

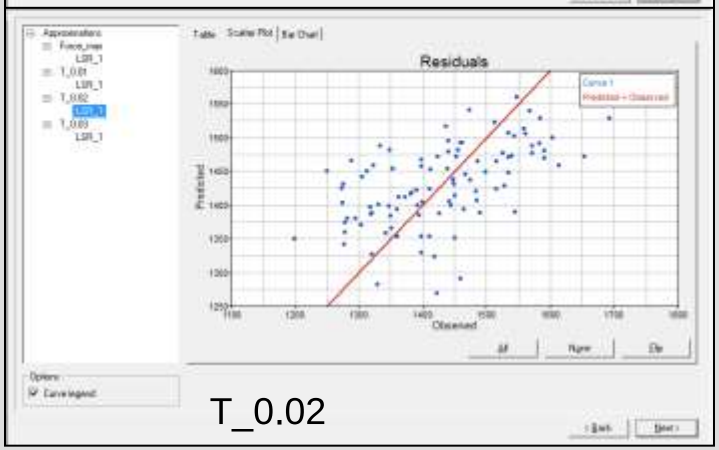
Runs	State	1a_1.S	2a_1.S	3a_1.S	1a_2.S	2a_2.S	3a_2.S	H1.S	H2.S	H3.S	H4.S	H5.S	4a_1.S
1	☑	0.0100000	0.0000000	-0.1333333	-0.4000000	-0.5714286	-0.7272727	0.0769231	0.0588235	0.0526316	0.0434783	0.0344828	0.03225
2	☑	0.0200000	-0.5000000	0.4333333	0.2000000	-0.1428571	-0.4545455	0.1538462	0.1176471	0.1052632	0.0869565	0.0689655	0.06451
3	☑	0.0300000	0.5000000	-0.5111111	0.8000000	0.2857143	-0.1818182	0.2307692	0.1764706	0.1578947	0.1304348	0.1034483	0.09677
4	☑	0.0400000	-0.7500000	0.0555556	1.4000000	0.7142857	0.0909091	0.3076923	0.2352941	0.2105263	0.1739130	0.1379310	0.12903
5	☑	0.0500000	0.2500000	0.6222222	-0.8800000	1.1428571	0.3636364	0.3846154	0.2941176	0.2631579	0.2173913	0.1724138	0.16129
6	☑	0.0600000	-0.2500000	-0.3222222	-0.2800000	1.5714286	0.6363636	0.4615385	0.3529412	0.3157895	0.2608696	0.2068966	0.19354
7	☑	0.0700000	0.7500000	0.2444444	0.3200000	-0.9387755	0.9090909	0.5384615	0.4117647	0.3684211	0.3043478	0.2413793	0.22580
8	☑	0.0800000	-0.8750000	0.8111111	0.9200000	-0.5102041	1.1818182	0.6153846	0.4705882	0.4210526	0.3478261	0.2758621	0.25806
9	☑	0.0900000	0.1250000	-0.6370370	1.5200000	-0.0816327	1.4545455	0.6923077	0.5294118	0.4736842	0.3913043	0.3103448	0.29032
10	☑	0.1000000	-0.3750000	-0.0703704	-0.7600000	0.3469388	1.7272727	0.7692308	0.5882353	0.5263158	0.4347826	0.3448276	0.32258
11	☑	0.1100000	0.6250000	0.4962963	-0.1600000	0.7755102	-0.9752066	0.8461538	0.6470588	0.5789474	0.4782609	0.3793103	0.35483
12	☑	0.1200000	-0.6250000	-0.4481481	0.4400000	1.2040816	-0.7024793	0.9230769	0.7058824	0.6315789	0.5217391	0.4137931	0.38709
13	☑	0.1300000	0.3750000	0.1185185	1.0400000	1.6326531	-0.4297521	0.0059172	0.7647059	0.6842105	0.5652174	0.4482759	0.41935
14	☑	0.1400000	-0.1250000	0.6851852	1.6400000	-0.8775510	-0.1570248	0.0828402	0.8235294	0.7368421	0.6086957	0.4827586	0.45161
15	☑	0.1500000	0.8750000	-0.2592593	-0.6400000	-0.4489796	0.1157025	0.1597633	0.8823529	0.7894737	0.6521739	0.5172414	0.48387
16	☑	0.1600000	-0.9375000	0.3074074	-0.0400000	-0.0204082	0.3884298	0.2366864	0.9411765	0.8421053	0.6956522	0.5517241	0.51612
17	☑	0.1700000	0.0625000	0.8740741	0.5600000	0.4081633	0.6611570	0.3136095	0.0034602	0.8947368	0.7391304	0.5862069	0.54838
18	☑	0.1800000	-0.4375000	-0.5740741	1.1600000	0.8367347	0.9338843	0.3905325	0.0622837	0.9473684	0.7826087	0.6206897	0.58064
19	☑	0.1900000	0.5625000	-0.0074074	1.7600000	1.2653061	1.2066116	0.4674556	0.1211073	0.0027701	0.8260870	0.6551724	0.61290
20	☑	0.2000000	-0.6875000	0.5592593	-0.5200000	1.6938776	1.4793388	0.5443787	0.1799308	0.0554017	0.8695652	0.6896552	0.64516

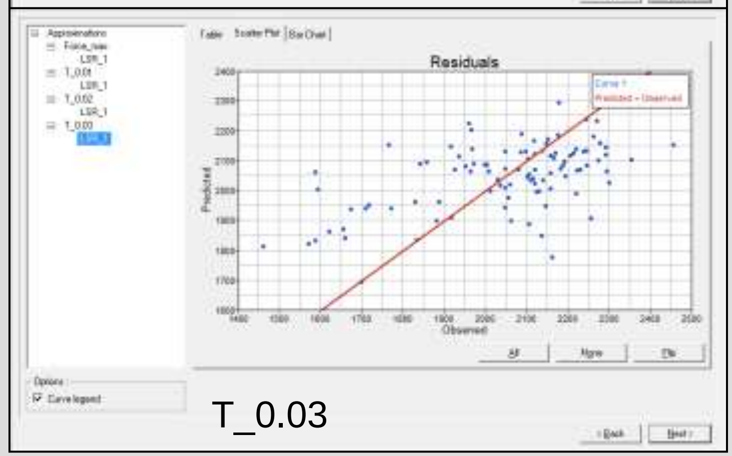
Design of Experiment (Approximation)

- Hammersly DOE Residual Plots – **Least Square Regression Method**





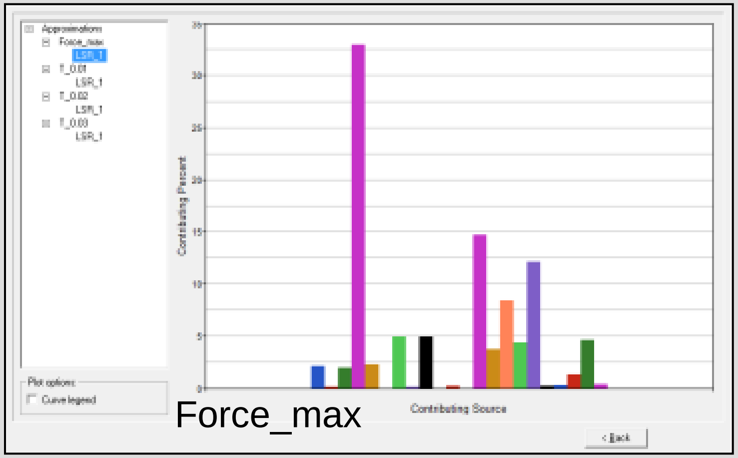




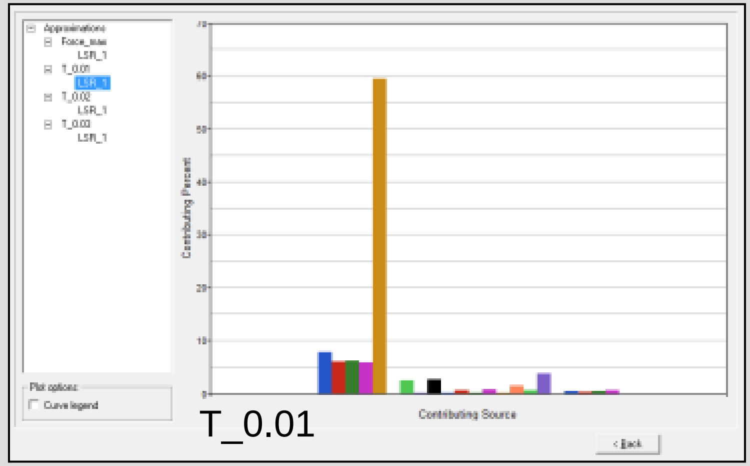
- A Least-square regression approximation was created to generate a simplified mathematical expression that best represent the responses. Clearly, this approximation method is not accurate enough due to the widespread scatter of points.

Design of Experiment

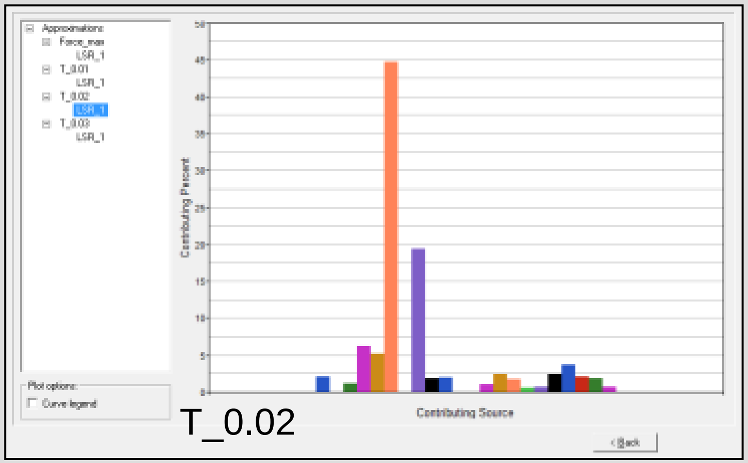
- Analysis Of Variance (ANOVA) Plots



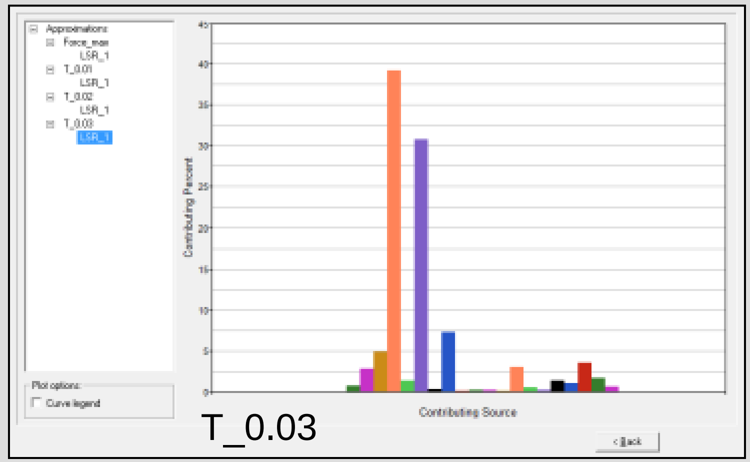
Force_max



T_0.01



T_0.02



T_0.03

- The Anova plots created helped to understand the relative importance of the design variables to the responses.

Design of Experiment

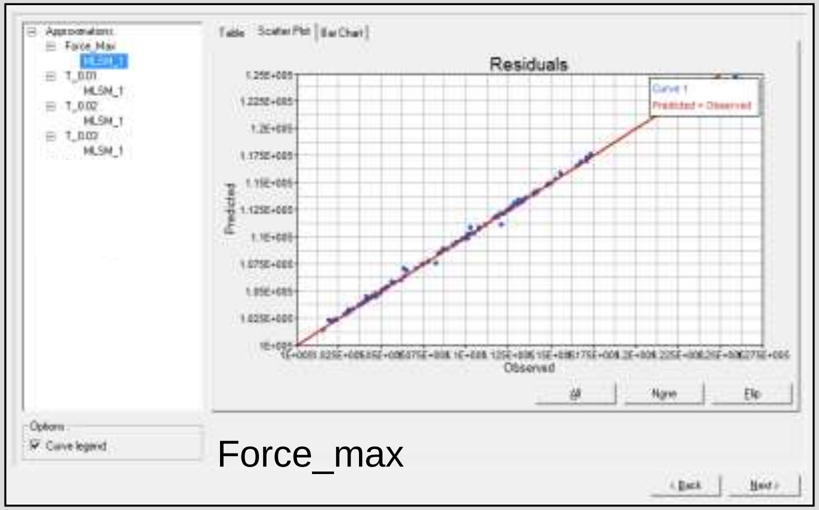
- With the aid of the ANOVA plot, the design variables which had little or no effect on the response were discarded. so, another DOE study was then carried out with just 7 of the existing 21 design variables. Now, 128 runs were set up.

- In addition, the approximation method was changed from Least-Square Regression to **Moving Least-Squares** method.

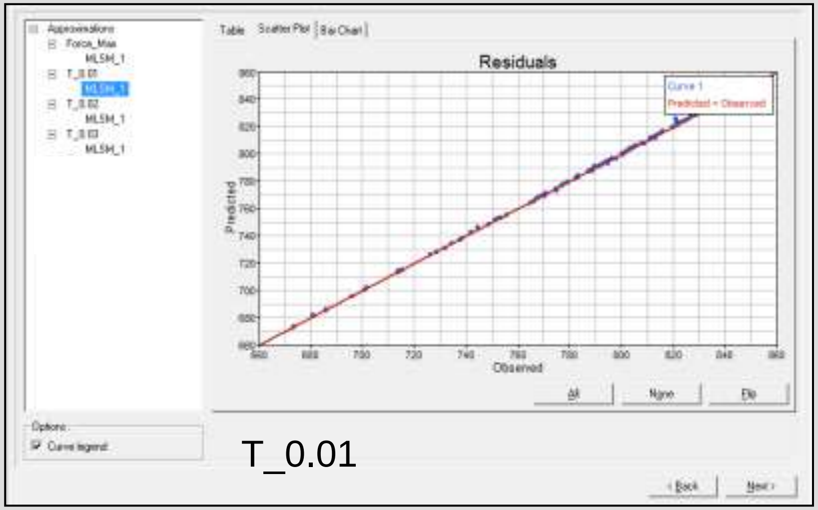
- This resulted to better approximation of the responses. (See next slide).

Design of Experiment

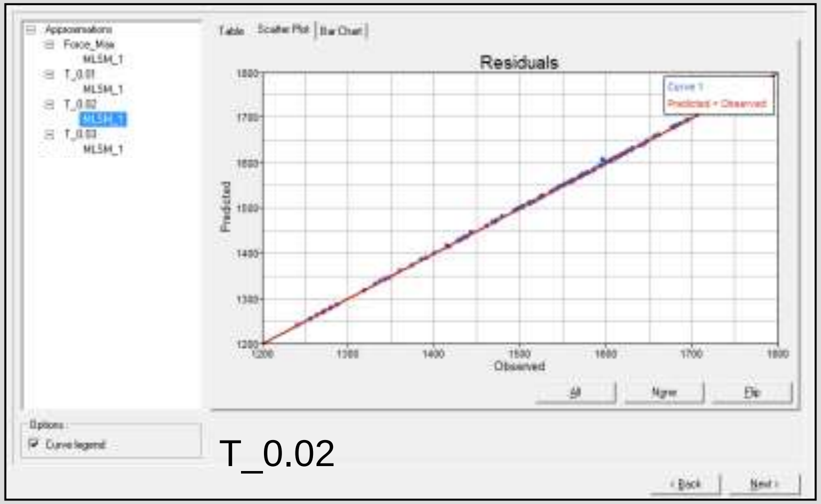
- Hammersly DOE Residual Plots – **Moving Least-Squares Method**



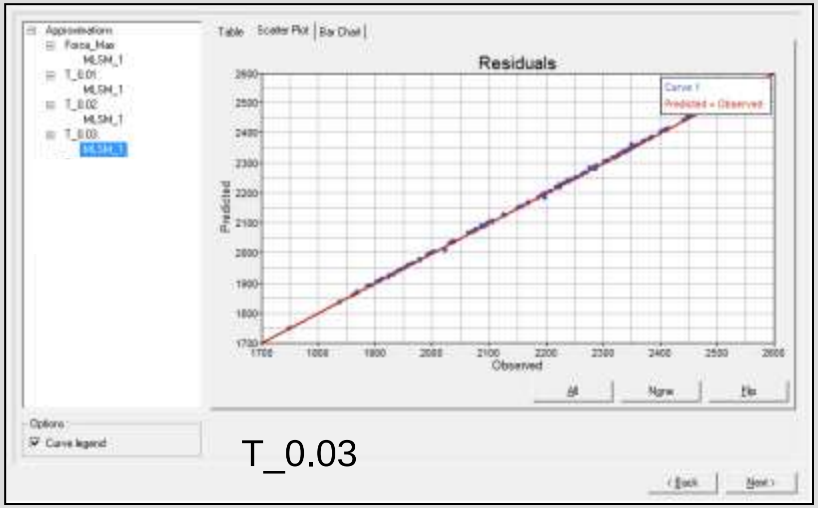
Force_max



T_0.01



T_0.02



T_0.03

Optimisation

- A **Sequential Quadratic Programming** optimisation based on the Moving Least-Square approximation was set up to see if a better design can be produced.
- The Objective was set to maximize the energy absorbed by the beam between 0 and 0.03s (T_0.03) which is the area under graph in that time range.
- Constraints were also set on the remaining responses:

Maximum Force over the whole time range	85kN ≤ F_max ≤ 106kN
Energy absorbed between 0 and 0.01s	T_0.01 ≥ 800J
Energy absorbed between 0 and 0.02s	T_0.02 ≥ 1500J

Optimisation Results

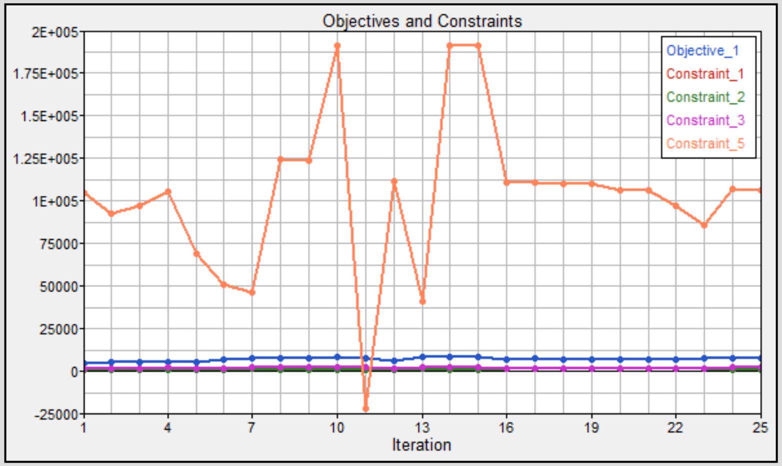


Fig 3a: Optimisation Iteration History plot

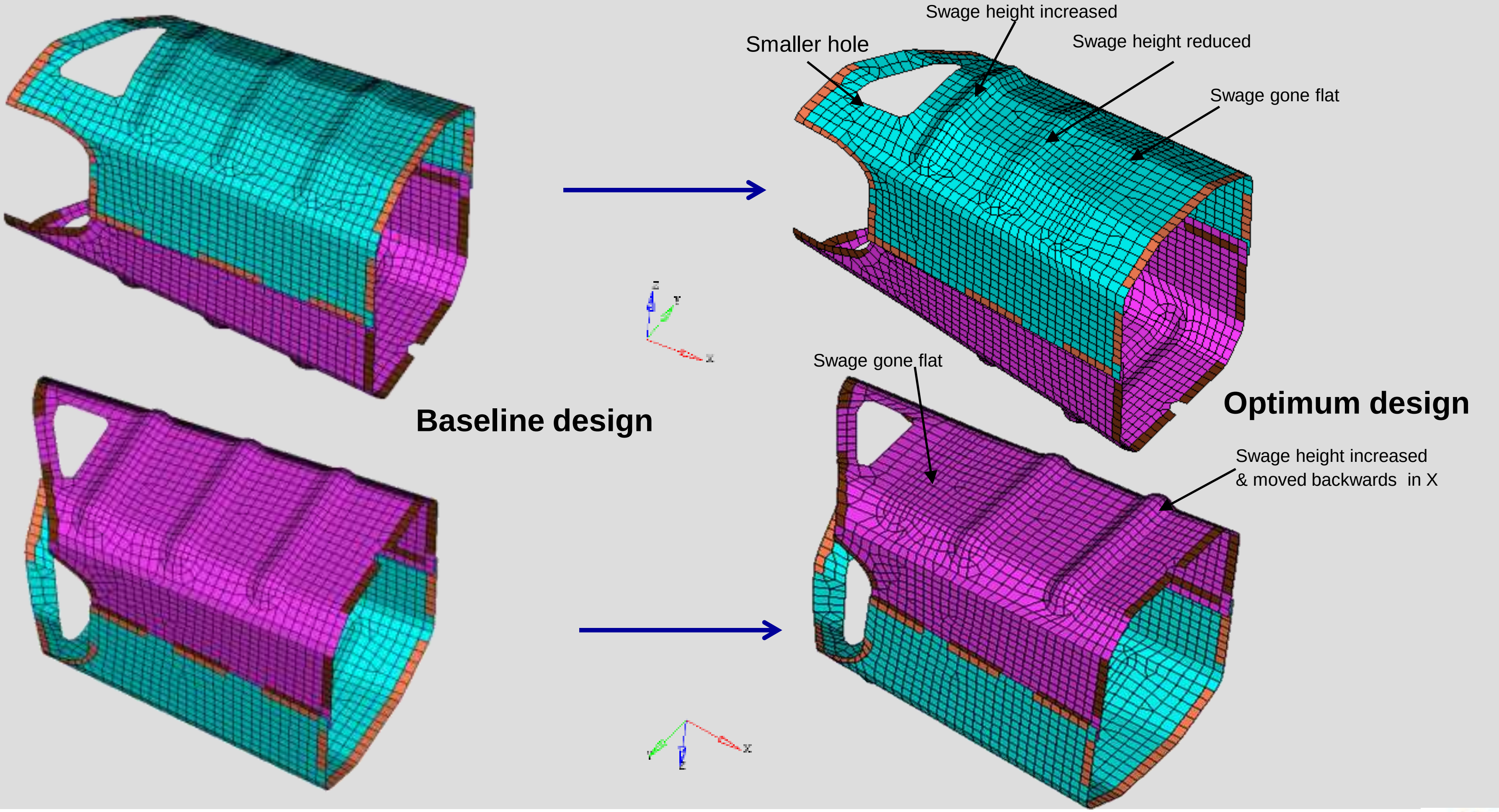
	T_0.03	F_min	T_0.01	T_0.02	F_max							
Iteration	Objective_1	Constraint_1	Constraint_2	Constraint_3	Constraint_5	2a_2.S	1a_2.S	3a_2.S	H2.S	5a_1.S	4a_2.S	6a_2.S
1	4829.3774	104613.26	791.92409	1671.9227	104613.26	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2	5118.7086	92182.538	833.08485	1741.5050	92182.538	-0.0222192	-0.3246121	0.3246121	0.0065792	-0.3246121	0.3246121	0.3246121
3	5351.7617	96636.412	832.74869	1784.7774	96636.412	-0.0898170	-0.1921509	0.3921509	0.0207244	-0.3921509	0.3201918	0.3921509
4	5610.5885	105283.74	848.57629	1913.5418	105283.74	-0.0900979	0.2604487	0.4612532	0.1452829	-0.4032928	0.3204016	0.1503106
5	5667.7621	68617.291	1035.1818	1634.6842	68617.291	-0.3518784	0.5931789	0.7036399	0.1731149	-0.6717563	0.6261585	0.0154765
6	6561.0684	50768.223	1039.5750	1816.7202	50768.223	-0.0326208	0.4644912	1.0000000	0.3674560	-1.0000000	1.0000000	-0.4012527
7	7846.4082	46275.589	1370.9243	2084.4449	46275.589	-0.1647993	0.2179233	1.0000000	0.3769687	-1.0000000	1.0000000	-0.2447060
8	7446.7165	124031.03	1116.5791	1953.2698	124031.03	-0.1530715	0.2829560	1.0000000	0.3990294	-1.0000000	1.0000000	-0.2834333
9	7457.3570	123781.12	1118.2180	1956.0630	123781.12	-0.1516882	0.2766620	1.0000000	0.3964701	-0.9991925	1.0000000	-0.2817275
10	8152.9828	190671.76	857.21817	2082.3223	190671.76	0.5379576	0.1499082	1.0000000	0.0310794	-1.0000000	1.0000000	-0.5689030
11	7441.6650	-22061.893	1023.9273	2124.9815	-22061.893	0.2859105	-0.3544013	1.0000000	0.0000000	-0.9113032	1.0000000	-0.2549089
12	5820.7974	110998.89	988.09272	1758.8352	110998.89	-0.2388297	-0.0990139	1.0000000	0.4497034	-1.0000000	1.0000000	-0.0616415
13	8106.9591	40969.588	1312.8313	2261.8961	40969.588	-0.0512947	0.0575309	1.0000000	0.3348386	-0.8780507	1.0000000	-0.1951229
14	8152.9828	190671.76	857.21817	2082.3223	190671.76	0.5379576	0.1499082	1.0000000	0.0310794	-1.0000000	1.0000000	-0.5689030
15	8152.9828	190671.76	857.21817	2082.3223	190671.76	0.5379576	0.1499082	1.0000000	0.0310794	-1.0000000	1.0000000	-0.5689030
16	7163.9304	110631.14	1492.5409	1410.3303	110631.14	-0.2204922	0.1989175	1.0000000	0.0000000	-1.0000000	0.9077324	-0.3376123
17	7219.1795	110477.61	1381.9145	1496.4022	110477.61	-0.1180942	0.1967916	0.9972932	0.0000000	-0.9942915	0.9217432	-0.3695360
18	7188.3440	110144.51	1443.5843	1449.6126	110144.51	-0.1767268	0.1984742	0.9975638	0.0000000	-0.9948623	0.9151452	-0.3504819
19	7188.3440	110144.51	1443.5843	1449.6126	110144.51	-0.1767268	0.1984742	0.9975638	0.0000000	-0.9948623	0.9151452	-0.3504819
20	7188.2364	106046.93	1440.9640	1473.6262	106046.93	-0.1741343	0.2033523	0.9837055	0.0000000	-0.9612095	0.9318328	-0.3422868
21	7188.1876	106326.78	1436.5772	1476.2416	106326.78	-0.1713328	0.2022531	0.9834903	0.0012446	-0.9621260	0.9325054	-0.3425523
22	7188.9720	97240.628	1487.4504	1498.0013	97240.628	-0.2152147	0.2098951	0.9660133	2.09e-04	-0.8738346	0.9582424	-0.3106084
23	7221.5595	85888.520	1500.4265	1565.3432	85888.520	-0.2295200	0.2158297	0.9421389	0.0000000	-0.7474001	1.0000000	-0.2788574
24	7543.6230	106878.84	1061.3960	1914.1162	106878.84	0.3433493	0.1510577	1.0000000	0.0000000	-0.8515487	1.0000000	-0.4801375
25	7563.0084	106034.00	1065.6802	1928.6749	106034.00	0.3472901	0.1196092	1.0000000	0.0000000	-0.8350920	1.0000000	-0.4586398

Best design

Fig 3b: Optimisation Iteration History table

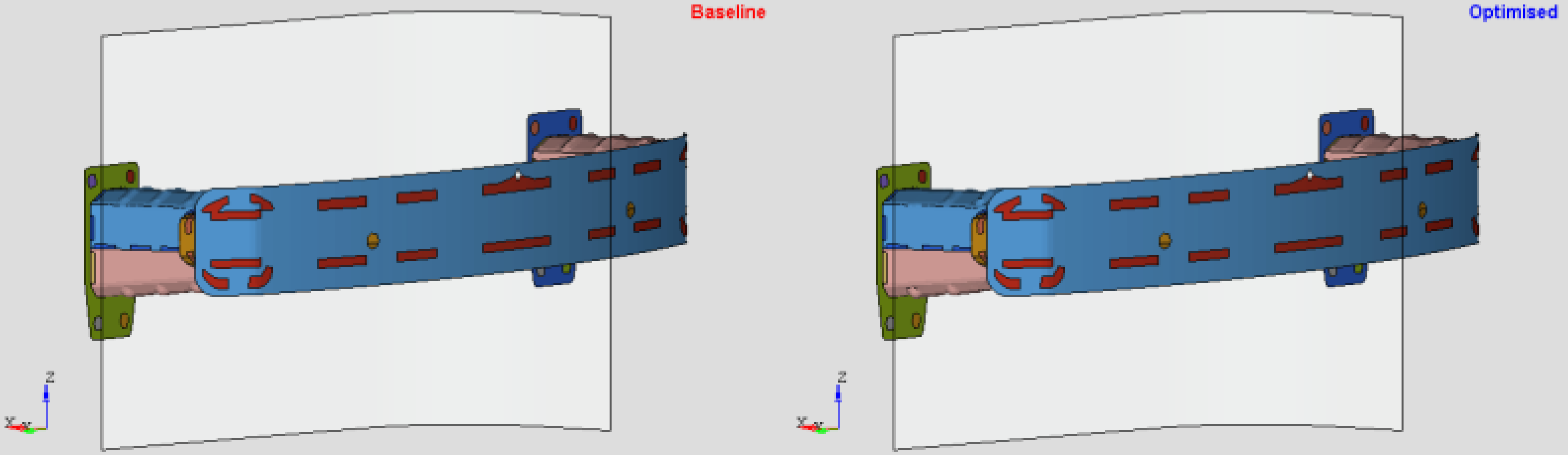
Optimisation Results

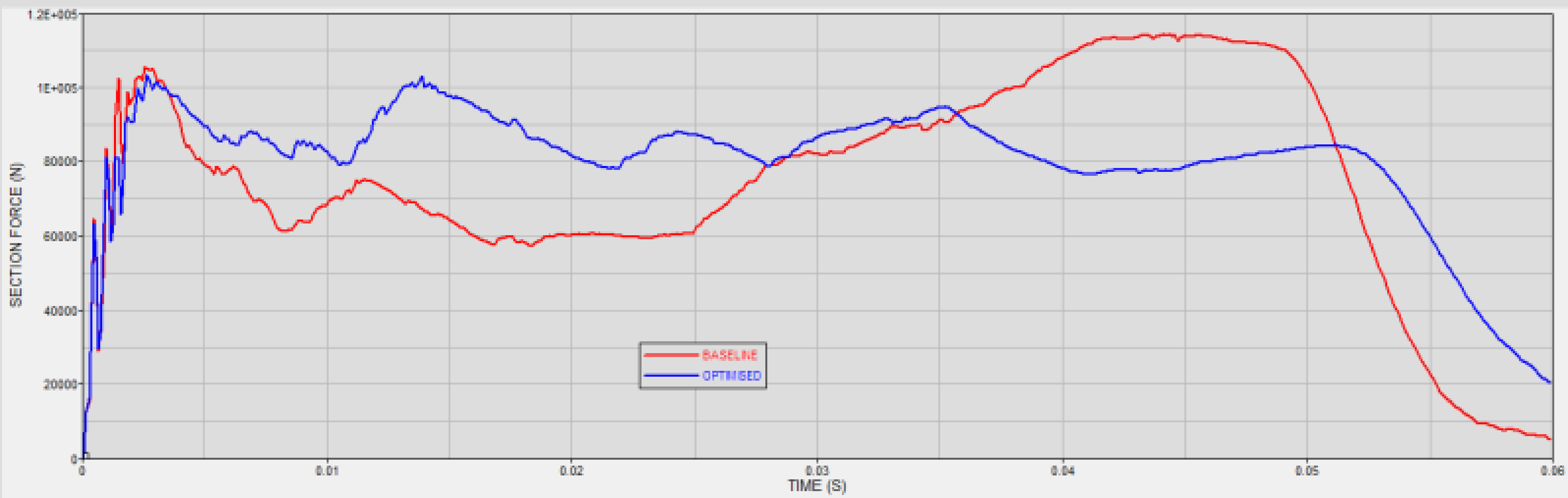
The shape multipliers generated from the optimisation are then applied to the model to morph the shapes to the optimised position. The resulting changes are shown below.



Optimisation Results

Comparison between Baseline and Optimised design





Summary

- Using the Analysis of Variance (ANOVA) plot, the effects of the Crush-can geometry on the Section-force of the Crash beam has been successfully studied and number of design variables reduced to a more manageable level for subsequent analyses.

- A Sequential Quadratic Programming (SQP) optimisation based on Moving Least-Square approximation has also helped to identify an optimum design solution reducing the average section force to a level that is acceptable to the customer.

- This analysis only covers the Thatcham low speed front offset barrier aspect of the full crash performance of the vehicle, there are several other legislative requirements that must be met by the vehicle and therefore the DOE analysis will be repeated to find the optimum design solution to achieve them.
- Once the beam has been fully optimised for all crash events at component level it is handed over to the OEM to assess it's performance in the full vehicle model.