Analysis and Optimization of Aluminum Automobile Side Door Design Using LS-DYNA® Implicit and LS-OPT®

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Abstract

Vehicle design and development involves various types of linear and non-linear finite element analyses. Using different solvers for different types of analyses is not always a cost-effective solution. Using one solver for multiple types of analysis saves cost as well as it allows sharing CAE models between various disciplines. Although LS-DYNA historically has been used for explicit analysis, recent enhancements in LS-DYNA Implicit enable it to be used for various implicit analyses.

This work focuses on the analysis and optimization of an automobile side door assembly made of aluminum, using LS-DYNA Implicit Solver for multiple load cases. A combination of Novelis's high formable and high strength aluminum alloys were used in the door design. Implicit load cases used for this analysis were – modal analysis, door sagging, door frame stiffness, and beltline stiffness.

LS-DYNA Implicit models were further used for setting up DOE and design optimization. LS-OPT tool was used to conduct multi-response DOE studies and optimization to minimize the door weight while meeting all the performance requirements. Additionally, the DOE runs results were combined with Excel cost model results to choose an optimal design that balanced the total mass of the door versus the cost to manufacture. A final validation simulation was run to demonstrate the optimized design met all expected performance requirements.

Introduction

During design and development of an automobile side door, several physical tests and CAE analyses are conducted to make sure the design meets specific performance requirements. CAE analysis includes stamping simulations and structural performance simulations. Parts like the door frame, door inner, door outer etc. are driven by various static stiffness load cases which can be solved with an implicit method; whereas parts like the side door beam is driven by side impact which are better handled by an explicit method. Historically, LS-DYNA has been used widely for explicit analyses such as quasi-static or dynamic crash analysis whereas, there are other popular solvers in the industry which are used for implicit and linear static load cases such as modal analysis, door sag, door frame stiffness etc.

Recent enhancements in the LS-DYNA Implicit solver enable it to be used reliably and efficiently for implicit analysis as well. Using a single solver for multiple types of FEA gives substantial modeling time and associated cost savings and facilitates model sharing between different disciplines of CAE. This paper focuses on the structural FEA analysis for on door assembly using LS-DYNA for the following load cases:

- Modal analysis (Free-Free)
- Door Sagging
- Door frame stiffness (Mid)
- Door frame stiffness (Corner)
- Beltline stiffness

LS-DYNA models were built for above load cases using recommended best practices from available reference literature (see Reference section for details). The baseline models were then used in an optimization study in LS-OPT. The optimization study included two steps:

1) DOE study and
2) Optimization.

Initially, the DOE study was conducted in LS-OPT using the appropriate meta-model and sampling method. DOE results provided insight about the relative sensitivity of each response to the various design variables. These results were further used for further optimization runs with definition of appropriate optimization constraints, responses and objective function.

The results of the optimization meta–model were coupled with cost models and used to select appropriate gauges and grades of material that minimized the overall cost of the door while minimizing its mass and cost. This resulted in a final design that showed a significant improvement over the baseline aluminum design assumptions as measured by the overall dollar spent per kilogram save when comparing this design to a similar design in competing materials. Additionally, the effects on mass & cost and relaxing specific stiffness targets were evaluated from the meta-model without the need for additional runs.

LS-DYNA Implicit, coupled with LS-OPT allowed the entire potential design space to be efficiently and quickly explored for the most cost effective and mass efficient designs, with minimal re-modeling required.

LS-DYNA Model Setup

LS-DYNA models were setup for Door stiffness load cases (Image 1) using LS-PrePost® and other pre-processors. LS-DYNA Implicit Solver was used to conduct analysis. LS-DYNA Implicit latest best practices were followed while setting up control cards, contacts and other LS-DYNA keyword definitions. Latest version of double precision LS-DYNA solver (R11.0) was used considering recent enhancements in implicit functionality, which gives accurate results and improved convergence.

Image 1: Door Load cases

Control Cards:
Control cards were defined as shown in Image 2. *CONTROL_IMPLICIT_GENERAL was used to activate the implicit solver. Initial time step size may be varied based on complexity and boundary conditions of the model. Non-linear solver was selected in *CONTROL_IMPLICIT_SOLUTION (nsolver=12) because there are non-linear entities present in the model such as contacts, non-linear material properties etc. Automatic time step control was used by activating *CONTROL_IMPLICIT_AUTO and defining a curve with the time step as a function of time. This option automatically adjusts the time step so that the time value of each key point on the curve is reached exactly. It also gives flexibility to reduce time step for critical points in the simulation. *CONTROL_IMPLICIT_DYNAMICS card was activated which helps to improve convergence.

```
*CONTROL_IMPLICIT_AUTO
$:    iauto    iteopt    itewin     dtmin     dtmax     dtexp     kfail    kcycle
          1        25         5    1.0E-2       -99       0.0         0         0
*CONTROL_IMPLICIT_DYNAMICS
$:    imass     gamma      beta     tdybir    tdydth    tdybur     irate     alpha
          1       0.6      0.38        0.0       0.0       0.0         1       0.0
*CONTROL_IMPLICIT_GENERAL
$:   imflag       dt0     imform      nsbs       igs     cnstn      form    zero_v
          1    5.0E-2          0         0         0         0         0         0
*CONTROL_IMPLICIT_SOLUTION
$:   nsolvr    ilimit     maxref     dctol     ectol     rctol     lstol    abstol
         12        11          0       0.0       0.0       0.0       0.0       0.0
$:    dnorm     diverg      istif   nlprint    nlnorm   d3itctl     cpchk
          1         0          1         1         0         1         0
*DEFINE_CURVE
$: X axis : Time                          (Units: Time)
$: Y axis : Maximum allowable timestep    (Units: Time)
$:
$:    label       sidr        sfa       sfo      offa      offo    dattyp     lcint
         99          0        0.0       0.0       0.0       0.0         0         0
$:            xvals                  yvals
       0.40000001            0.50000000
       0.50000000          5.0000001E-2
        1.0000000            0.50000000
$
```

Image 2: LS-DYNA Control Cards

Contacts:
*CONTACT_AUTOMATIC_SINGLE_SURFACE_MORTAR card was used to define self-contact for the model. MORTAR option was added because is a specialized option which provides robustness and accuracy in implicit analysis. All initial penetrations were checked and removed. IGNORE=1 was used in contact card. All the spot-welds, structural adhesives, hem adhesive and mastic was modelled with solid Hexahedron elements with ELFORM=1. For spot-welds and adhesives tied contact was defined. The following contact card was used:
*CONTACT_TIED_SHELL_EDGE_TO_SURFACE_CONSTRAINED_OFFSET

*CASE Keyword:
In order to have a single model for multiple load cases, subcases were created in the main model using *CASE keyword (Image 3). Appropriate boundary conditions were assigned for each subcase.

```
*CASE                                    *CASE
$PR_TITLE Door_sag                       $PR_TITLE Frame_mid
$:  caseid        jobid                  $:  caseid        jobid
          1Door_sag                                3Frame_mid
$:    cid1                                $:    cid1
          1                                          3
$                                        $
*CASE                                    *CASE
$PR_TITLE Frame_corner                   $PR_TITLE Beltline
$:  caseid        jobid                  $:  caseid        jobid
          2Frame_Corner                            4Beltline
$:    cid1                                $:    cid1
          2                                          4
```

Image 3: LS-DYNA *CASE keyword

Optimization Setup

Gauge optimization study was conducted on above explained LS-DYNA door model described above using LS-OPT. The objective of the study was to understand the sensitivity of responses to various design variables and come up with optimal combination of gauges which would give lightest design solution which meets all the performance requirements. This study was conducted in two steps: 1) DOE study and 2) Optimization.

DOE Study:
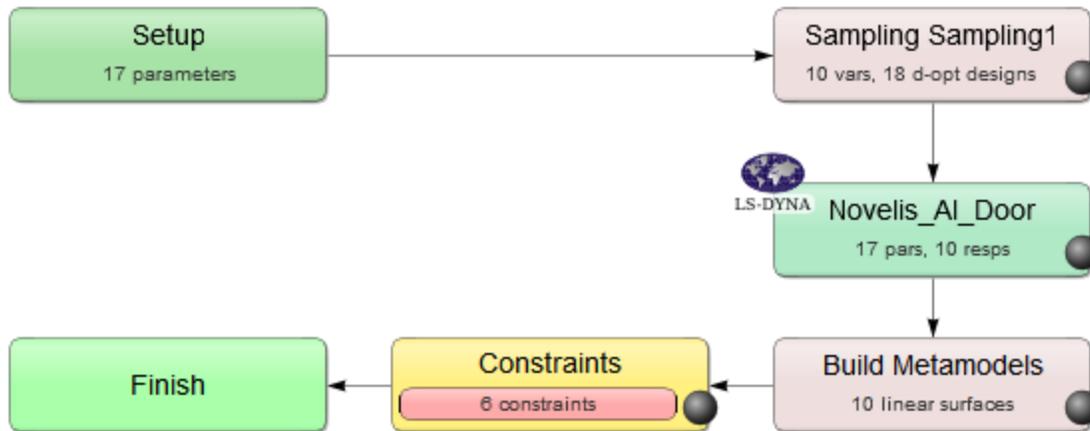
Image 3: LS-OPT Flowchart for DOE Study

Initially, the DOE study was conducted in LS-OPT using the 'Polynomial' metamodel and 'D-optimal' point selection method. Image 3 above shows the LS-OPT flowchart for DOE setup. Design variables were defined in the Setup box. LS-OPT automatically detects *PARAMETER cards from LS-DYNA models and defines them as design variables. In this case, gauges of various parts in the assembly were defined as design variables. Each design variable was assigned upper and lower limits. Image 4 shows list of design variables. Responses and constraints were defined for various load cases. LS-DYNA executable path and command line were defined in Stage (Novelis_Al_Door) box. The DOE results provided insight about the relative sensitivity of each response to the various design variables.

Type		Name	Starting	Minimum	Maximum
Constant	∨	Chk_Rf	2		
Continuous	∨	D_Innr	1.2	0.9	1.5
Constant	∨	D_Otr	0.95		
Constant	∨	Hng_Mat	1185598		
Constant	∨	Hng_Mod	210000		
Constant	∨	Ltch_Rf	1		
Continuous	∨	Mrflg_Rf	1	0.9	2.5
Continuous	∨	Otrblt	1	0.9	2
Continuous	∨	LHng_Rf	2.2	1	3.5
Continuous	∨	UHng_Rf	2.2	1	3.5
Constant	∨	Ltap	3		
Constant	∨	Utap	3		
Continuous	∨	GRC	1	0.9	1.5
Continuous	∨	Halo1	1.5	0.9	2.5
Continuous	∨	Halo2	1.5	0.9	2.5
Continuous	∨	Halo3	1.5	0.9	2.5
Continuous	∨	Halo4	1.5	0.9	2.5

Image 4: Design Variables in LS-OPT for DOE Study

Optimization:

The Optimization model was built in LS-OPT (Image 5). The initial DOE results helped to refine the upper and lower limits of design variables for further optimization runs. The objective function was defined along with histories, responses, optimization constraints for each load case. For optimization, the following two approaches were used:

1. Metamodel-based optimization with 'Sequential' strategy
2. Metamodel-based optimization with 'Sequential with Domain Reduction' strategy
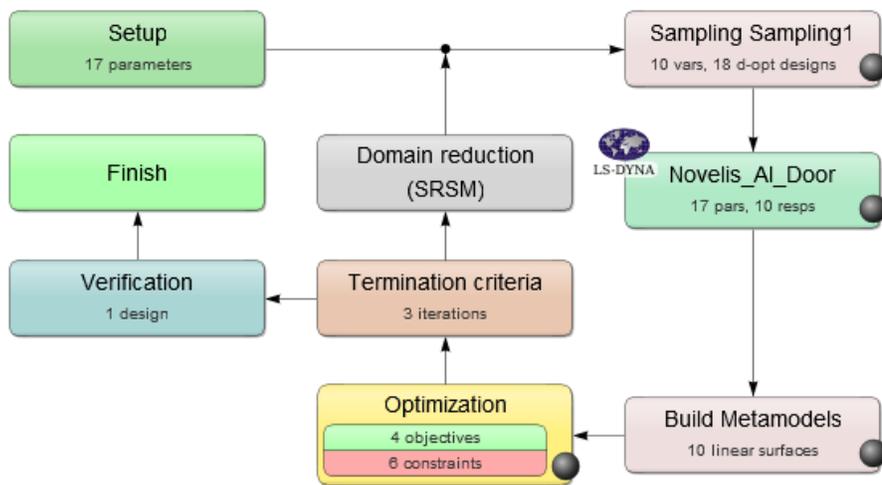
Image 5: LS-OPT Flow Chart for Sequential with Domain Reduction Metamodel

LS-OPT results were post-processed using LS-OPT Viewer. Various post-processing tools like simulation, scatter plots, simulation correlation matrix (Image 6), metamodel 2D-interpolator, metamodel sensitivity (Image 7), metamodel response surface were used to understand the sensitivity of design variables and finalize the optimal design.
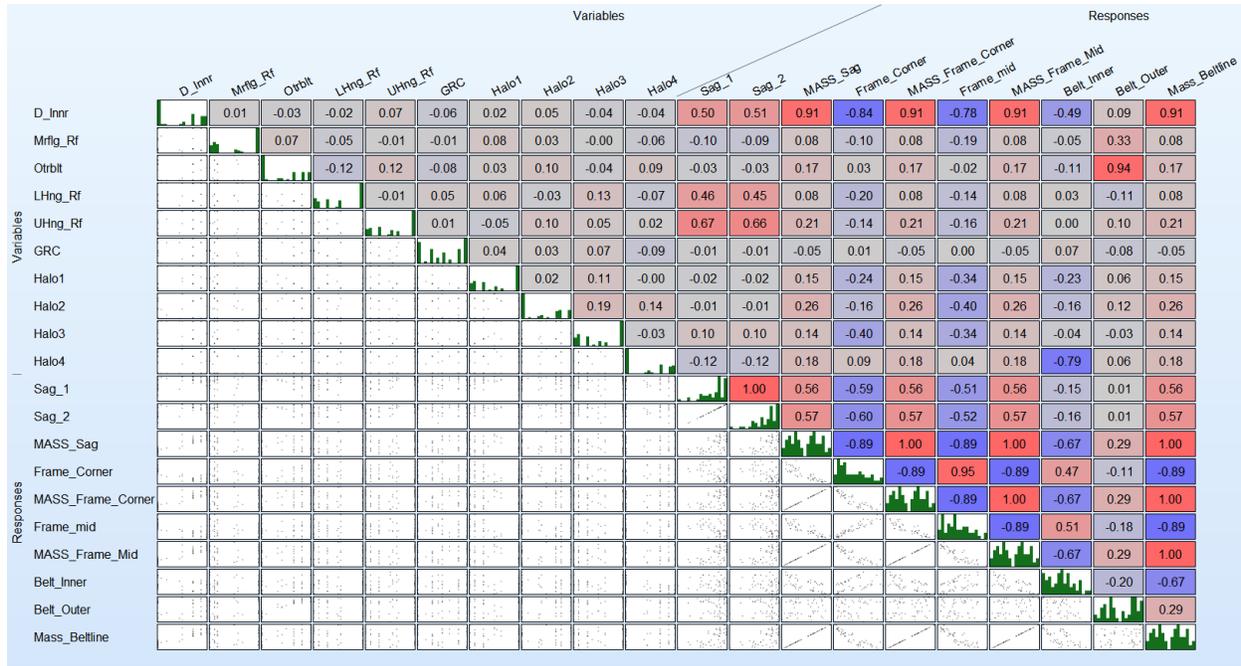
Image 6: Correlation Matrix (LS-OPT post-processing)
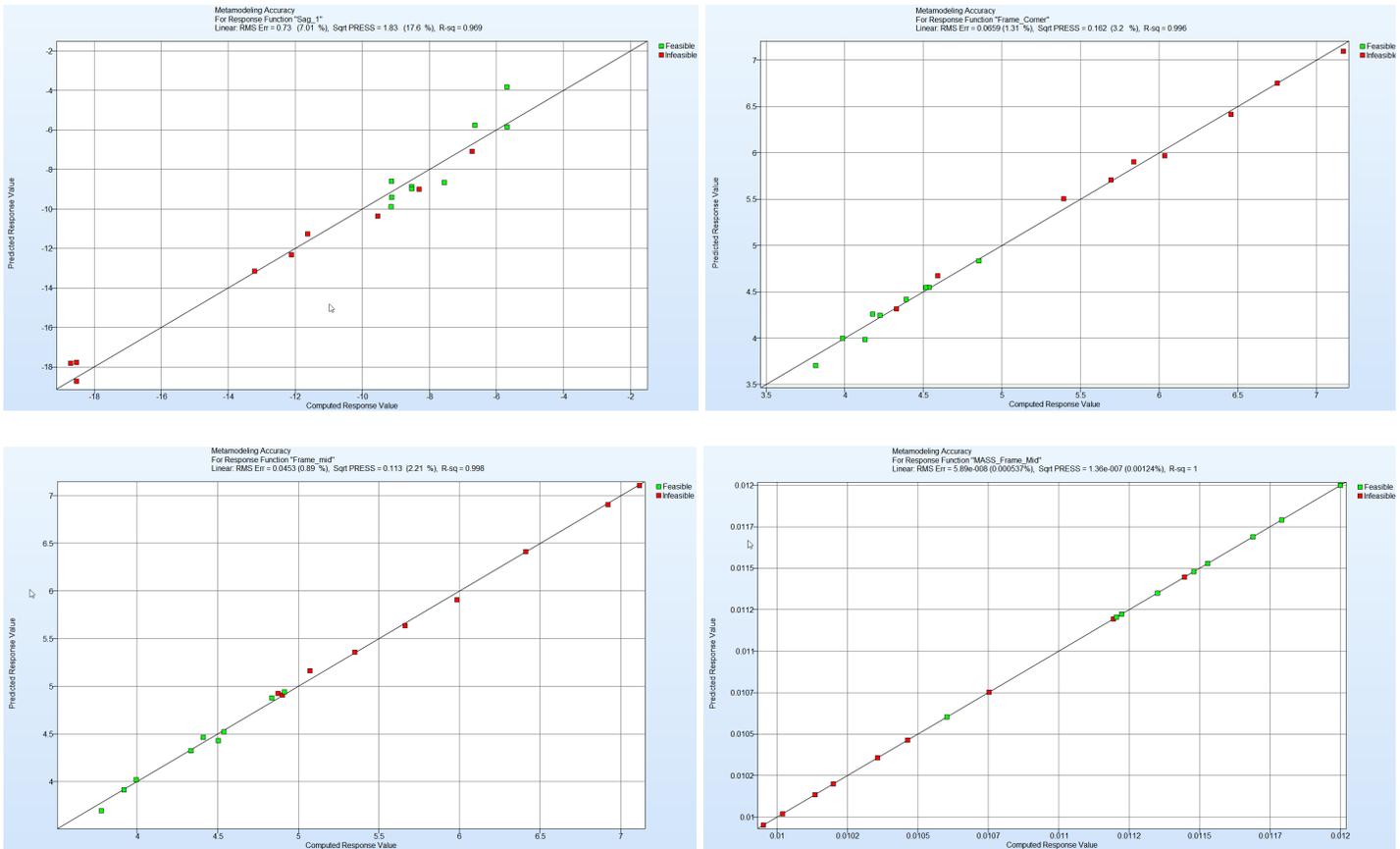
Image 7: Metamodel Accuracy Plots for responses

Additionally, DOE runs results were combined with Microsoft Excel cost model results to choose an optimal design that balanced the total mass of the door versus the cost to manufacture. A final validation simulation was run to demonstrate the optimized design met all expected performance requirements. Effect on mass/cost and relaxing performance targets was evaluated using a metamodel without a need of running more CAE runs.

Results:

Table below (Table 1) shows summary of results for baseline and optimized model for above mentioned load cases. It can be observed that Optimized design performs better than the baseline. In addition, optimzed design is also ligher than baseline by 1.01 kg (9.2 %)

Loadcase			Deflection (mm)					
			Baseline		Optimized Design		Target	
			Max (Loading)	Residual (Unloading)	Max (Loading)	Residual (Unloading)	Max (Loading)	Residual (Unloading)
Beltline Stiffness	Inner		0.73	0	0.74	0	Inner + Outer = 5	0
	Outer		0.96	0	0.97	0		0
Frame Stiffness	Mid		5.02	0	4.81	0	5	0
	Corner		5.25	0	4.87	0	5	0
Door Sag (5 ° Deg Open)			16.43	6.7	7.69	1.19	8	2
Total Mass			10.94 kg		9.93 kg		-	

Table 1: Summary of results

Summary

LS-DYNA Implicit and LS-OPT helped to optimize automobile side door design to a lightweight and cost-effective solution. Use of *CASE keyword enabled to have a single model for multiple load cases. LS-OPT enabled to run large number of simulations through DOE. This exercise gave ~ 1.04 kg mass savings in the door which was ~ 9.2% of the baseline mass. Using same solver for multiple types of analyses saved considerable modeling time. Same model was used in LS-DYNA explicit solver later for other highly non-linear load cases such as FMVSS214 static side impact with few updates in control card parameters.

Next Steps

This approach is to be developed though further work which would include but not limited to following steps:
- Include forming data in the simulation
- Include more load cases such as dent resistance, oil canning, wind overload etc.
- Include geometrical changes in the optimization (Shape Optimization)
-

References

[1] "Tips & Tricks for successful implicit analysis with LS-DYNA" – Tobias Erhart (DYNAmore Gmbh)
[2] "Non-Linear analysis using LS-DYNA Implicit" – Anders Jonsson (DYNAmore)
[3] "Roof-Crush Analysis of the Volvo XC40 using the Implicit Solver in LS-DYNA" 12ᵗʰ European LS-DYNA conference 2019.
[4] "Re-Using Crash Models for Static Load Cases with Minimal Effort", 15ᵗʰ international LS-DYNA conference
[5] "Guideline for implicit analysis using LS-DYNA" - DYNAmore