Automatic Shape Optimization of a Rivet Coupling modeFRONTIER and LS-DYNA

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1 Abstract

Increasingly stringent government fuel consumption legislation and evolving consumer preferences are making a difference. Automakers are achieving weight reduction by replacing lighter materials such as aluminium, magnesium and advanced composites as well as making vehicle design changes.

Therefore a maximum flexibility of the used materials is necessary and new joining techniques are constantly developed.
Self-pierce riveting technology is a relatively new fastening technique. It has become a potential joining approach for aluminium alloy structures in the automotive and aerospace industry owing to their advantages over conventional fastening methods, such as spot welding.

The advantage of a self-piercing riveted joint in contrast to other joining methods such as spot-welding is to combine materials with different properties such as aluminium and steel.
Also, the joining process of self-piercing rivets does not affect the microstructure and thus the properties of joined materials.

Failure of a joint depends on various factors such as the geometry of joint configuration, sheet strength that are joined, rivet material used, cracks developed during joining, and many other.

This activity summarize a work divided into three stages of work. In the first stage, a 2D simulation of riveting process is carried out over two sheets, made of steel and aluminium. In the second stage of work, it was conducted a numerical-experimental correlation in order to validate the simulation results. In the third stage, the rivet and die virtual models were parameterized in order to perform a shape optimization.

Numerical simulation has been used to investigate the riveting process. LS-DYNA® is a powerful tool for performing an adaptive meshing simulation to acquire a higher accuracy of results and to avoid high element distortion. The main goal of the simulation has been to locate the critical areas in which crack and fracture occurs in the original configuration. The study has been carried out to guarantee the integrity of the joining process.
The target of the project has been to develop an automatic and integrated approach to study the better rivet-die geometrical shapes.

2 Introduction

Modern vehicles are made of different material types: steel, aluminium, magnesium, plastic. As conventional spot welding cannot be used to join part made by different material, a new kind of technology suitable for this purpose is the self-piercing riveting. This is mainly used in automobile and aircraft industries, and consist in a single-step process of joining without any predrilled holes. A semi-tubular rivet made of high strength steel is used to make a joint between sheets.
The simulations were performed using an explicit-implicit solution technique with mesh adaptivity.

LS-DYNA® is a suitable tool to simulate the SPR process due to several reasons:

- adaptive meshing features
- several material models implemented
- robust contact algorithm
- springback analysis.

Numerical simulation with LS-DYNA virtually assess the joining quality, and permit to examine stress, force and deformation during joining.

After virtually testing the original configuration provided by the manufacturer, the rivet-die geometrical shapes were automatically modified in order to find a better solution.

The current activity will show the main aspects regarding the development of an automatic approach to execute these tasks.

3 SPR model description

The SPR joining technique relies on creating a mechanical interlock by flaring the hardened steel rivet shank, after it pierces a second sheet in joining a two-sheet assembly. The technique is not restricted to joining a two-sheet assembly, as it may be used to join three or more sheets comprising different materials in a single operation.

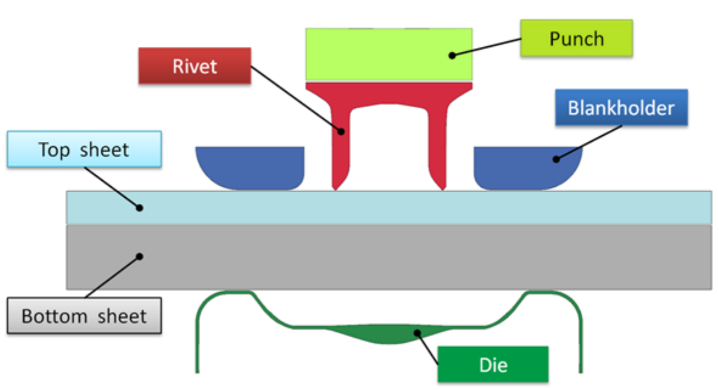

Fig.1: SPR tool setup.

Self-piercing riveting is a large-deformation process that involves piercing. The self-piercing riveting process can be summarized by four steps:

1. clamping: the blankholder presses the two sheets against the die, and then the rivet is gradually pressed into top sheets
2. piercing: the punch pushes the rivet into the top sheets
3. flaring: the material of the lower sheet flows into the die and the rivet shank begins to flare outward, forming a mechanical interlock between the upper and lower substrates
4. punch release: once the punch is retracted, the finished joint is achieved with the fastener properly seated in the sheets.

The process comprises many pairs of contacts between the punch, blankholder, rivet, top sheet, bottom sheet, and die.
The rivet material is a boron steel, top sheet is a dual phase steel, while the bottom sheet is an aluminium alloy.
Blankholder, punch and die were treated as rigid bodies.
Regarding contact interfaces, six pairs of contacts have been created to handle the friction distinctly. For the 2D simulations conducted *CONTACT_2D_AUTOMATIC_NODE_TO_SURFACE contact were chosen.

4 Frictions and materials calibration

Friction coefficient and material properties were not easy to set for simulation for the following two main reasons:
the materials data received by the customer concern tensile test and do not taking account treatments and machinery
the friction typology change during the process.

Preliminary simulations conducted have shown that friction play an important role in the penetration of rivet into sheets and has an influence on the results of the simulation. In particular, final shape of the rivet shank and the part of the top sheet in contact with the tip of the rivet shank is influenced by friction.

In order to find the correct parameters to use in the simulation, frictions and materials were parametrized and a modeFRONTIER workflow was build.

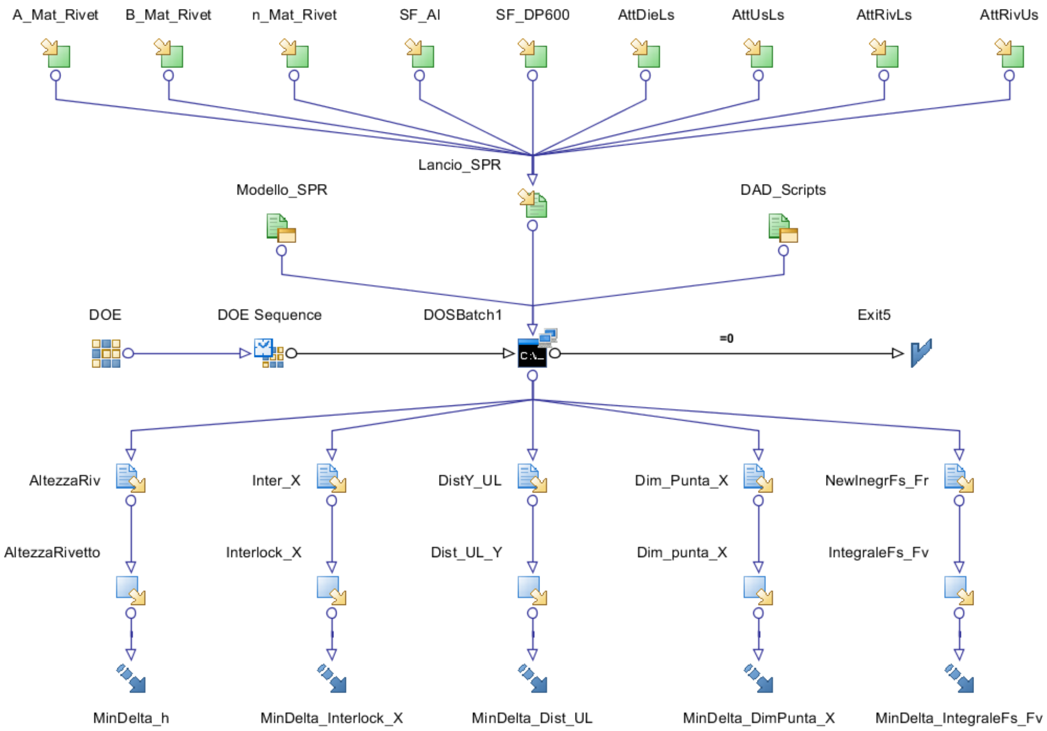

Fig.2: Example of modeFRONTIER workflow used to perform the model calibration

Experimental laboratory test results were carried out to define all the materials and friction coefficients using the modeFRONTIER Integration and Design Optimization software.

For rivet material is being used Material Type 98 implementing Johnson/Cook strain sensitive plasticity, in which the flow stress is expressed as follow:

$$\sigma_y = \left(A + B\bar{\varepsilon}^{p^n}\right)\left(1 + C\ln\dot{\varepsilon}^*\right)$$

It is used for problems where the strain rates vary over a large range. The values of the input constant A, B and n define respectively the yield stress and hardening parameter and were set as input variable to find the correct material, considering treatment and machinery.
The same procedure was implemented for the aluminium (bottom sheet) and steel (upper sheet) but using elasto-plastic materials Material Type 24 and parameterizing the stress versus plastic strain curves.

5 Adaptive meshing

During riveting simulation, high element deformation occurs and can cause error termination. To avoid this, a 2D remeshing technique was used.
In particular, this capability is called rezoning and is accomplished in three steps:

1. generate nodal value for all variables to be remapped
2. rezone one or more materials
3. Initialize remeshed regions by interpolating from nodal point values of old mesh.

Important card to set this feature in LS-Dyna environment are *CONTROL_ADAPTIVE, *CONTROL_ADAPSTEP, *PART_ADAPTIVE_FAILURE.

6 Post processing

As said in the previous paragraph, the mesh change during simulation, thus the nodes ids change continuously and is difficult to measure a distance between two nodes in automatic way.
For this reasons, is being created an ad hoc software that recognize the geometrical characteristics at the end of riveting simulation and make a comparison with the section cut of the image captured in the experimental test.

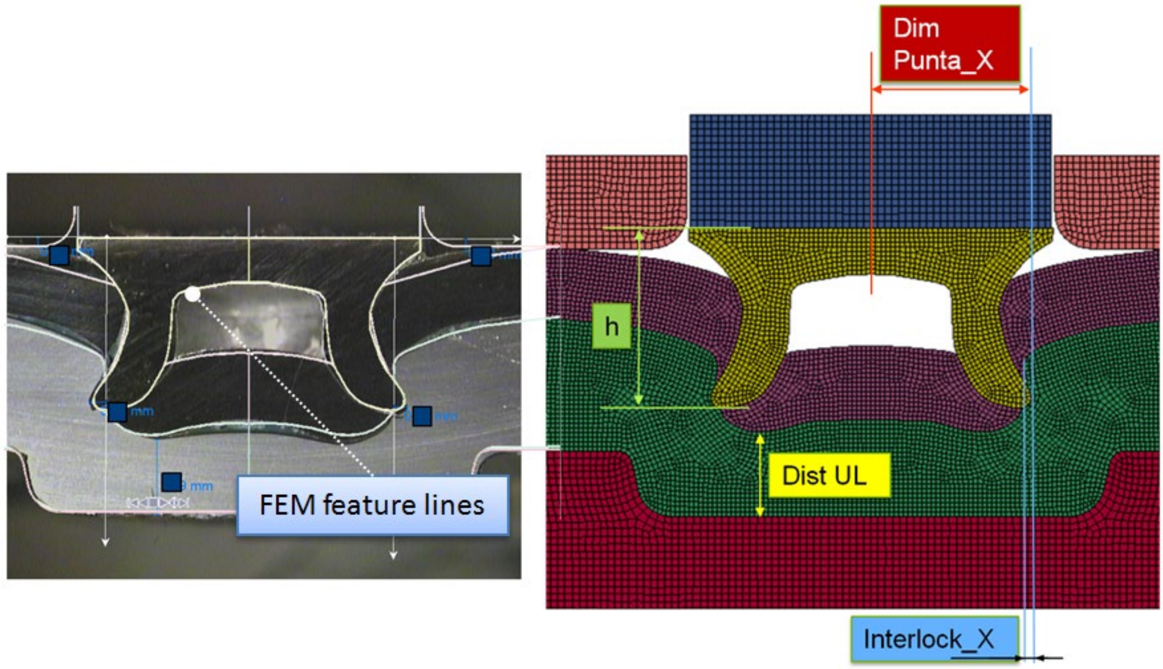

Fig.3: Overlapped image - Experimental vs. Numerical

The characteristic chosen to make the comparison are highlighted in fig 3.
Practically, during the post processing phase, the software have to compare: interlock, rivet deformed height, distance between upper sheet and lower sheet and maximum rivet diameter calculated on the rivet tails. In addition the post processing have also to compare riveting force.

7 DOE sensitivity analysis

Parametrical study were conducted to understand how friction value among parts and material characteristics affect the joining results.

By means of this system, a DOE sensitivity analysis was performed in order to:
Investigate material changes caused by treatments and machinery
Calibrate friction coefficient
Find correlation among objective functions verifying possible redundancy, for select independent function to use in the optimization phase
Find correlation among input variables and objective functions, to know how the system reacts to an input variable perturbation and define the ones that have major influence on objective function.

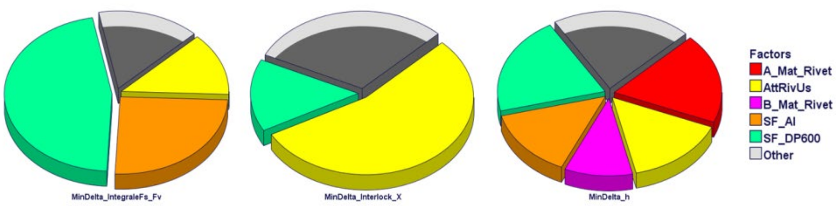

Fig.4: Overall Student Chart – Output vs. Input correlation

The Overall Student Chart highlights, by means of pie charts, the influence of each input (slice) on each output (pie).
In this case it emerges that the friction between rivet and upper sheet is very influencing for all objectives, in particular for the interlock.
To match the experimental test force, instead, the most important parameter is the top sheet material scale factor on stress-strain curve.
Rivet deformed shape is affected by all input variables investigated, practically in the same measure.

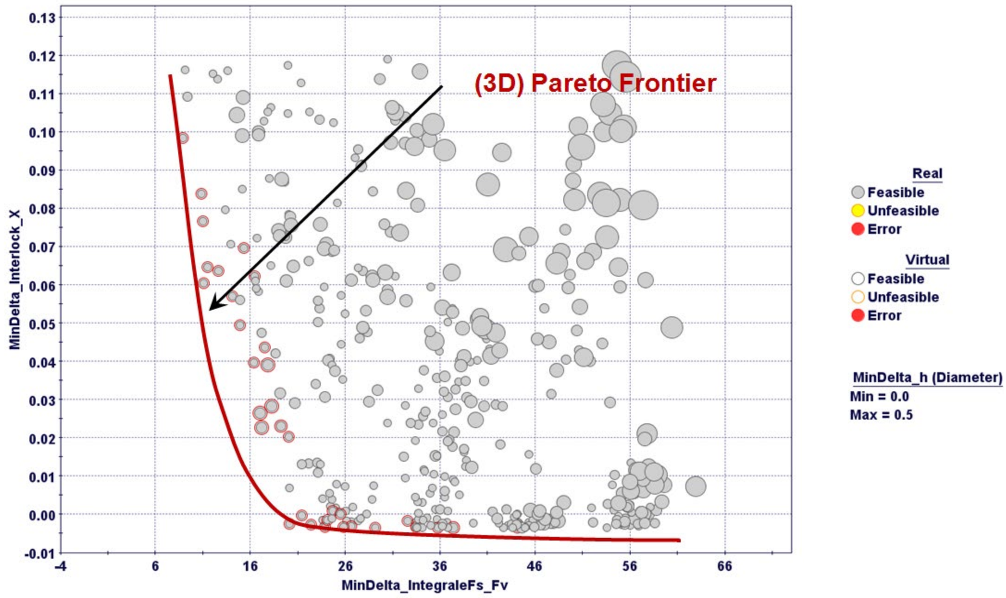

Fig.5: Trade-Off Objective Functions

To choose the best combination of the input variables that match the experimental test is being made a trade-off among three objective function.
In fig.5 is possible to see the data in three dimensions. It can be clearly noticed that the best designs are those close to the Pareto curve (best compromise interlock vs. riveting force), with small diameter (rivet deformed height).
For validate the parameter to use in the simulation are being carry out the following tests:

- Upper and lower sheet thickness variation
- Joining a three-sheet assembly
- Different rivet geometry.

The simulation results have shown a good agreement with laboratory tests and so the data were used to perform the optimization phase.

8 Optimization strategy definition

At this point we have a simulation that reacts with a wide correlation margin to the real riveting process.
We can modify the shape of the rivet and die and see what effects they produce on the junction mechanism.
In particular, it was decided to change the angles of the tail, the thickness and the head shape for the rivet, while for the die the morphing parameters are: clew's height, loop line radius, diameter and deep.

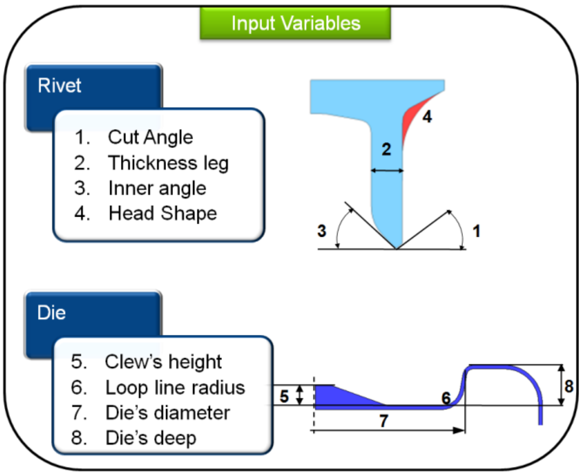

Fig.6: Morphing input variables

The goal of the optimization phase is to find designs that satisfied the following objectives:

- Interlock maximization, to improve joining resistance
- Riveting force minimization to reduce risk of joining failure
- Reduced plastic deformation on the bottom sheet to avoid bottom cracks
- Reduced rivet stress to avoid fracture on the rivet tails

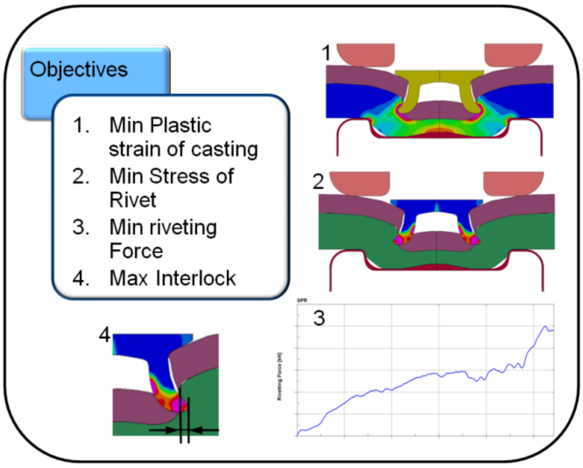

Fig.7: Morphing objective functions

In order to perform the optimization, modeFRONTIER has been used. modeFRONTIER is a state of the art multi-objective and mullti-disciplines optimization software.
In the presented work, the input variables are the morphing operations, so a change in the value implies a modification of the rivet and die shapes.
By means of the "sh node" it is possible to invoke both LS-DYNA solver that submits the analysis and LS-PrePost that reads the output files and generates further result files suitable for mF interpretation.
Such results are values that mF handles and, after some internal optimization process, modifies as modeFRONTIER input variables to achieve the target outputs. Extracted values can be also managed inside a calculator node where further operations can be performed.

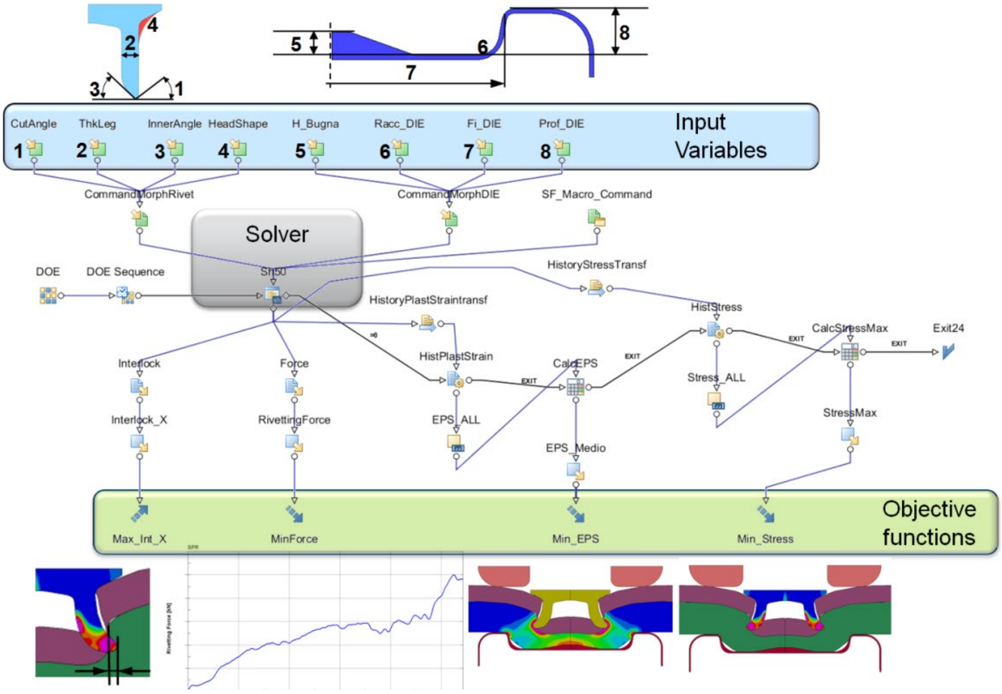

Fig.8: Logic flow implementation

By looking at the workflow in fig 8, it is possible to identify all the processes. Starting from above it is possible to see the input variables related to the morphing phase; a transfer file is created and passed to the LS-DYNA node. The support file folder, containing all files needed for the simulation and for the post processing also converges at this node. Moving forward in the flowchart, we can find the output template node needed to read the simulation results. Output, the objective functions that have to be to minimized or maximized to achieve the target results.
Due to a large amount of informations related to the performed tasks, the optimization results and the discussion will be the subject of a further article that will come out shortly.

9 Summary

The final goal of the activity is to design the rivet, die and the riveting process. Actually, the car makers choose the rivets from the supplier catalogue and the approach is "passive"; clearly the supplier pushes the already existing rivet geometries in order to avoid new dies machining and production process set up. But, probably, the catalogue doesn't include the optimum rivet for the specific application.
The developed methodology permits to identify, between the feasible geometries, the best shapes for the rivet and the die from the joining process point of view avoiding failures and maximizing the junction strength.