Modelling the Strength of an Aluminium-Steel Nailed Joint

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Abstract. For multi-material applications in automotive industry, a cast aluminium (upper layer) and dual-phase steel (lower layer) superposition joined with High-Speed Nailing process is investigated through an experimental vs numerical framework. Using FORGE® finite-element software, results from joining simulations have been inserted into models in charge of nailed-joint mechanical testings. Numerical Shear and Cross-tensile tests are compared to experimental ones to discuss discrepancy and possible improvements.

INTRODUCTION

Multi-material structures have become one of the main challenges of automotive light weighting [1]. It implies drastic changes of methodology at the design and manufacturing stages of the vehicle. Thus finite element simulation could provide interesting tools for engineers to distinguish materials configuration which are joinable from those which are not, due to inappropriate material thickness or extended mechanical properties. Investigations conducted in literature mostly focus on joining stage simulations [2]–[4] but joint strength predictability remains the biggest concern for industrial applications. On the basis of experimental and numerical nailings performed in the following superposition - cast aluminium (2.5mm) / dual-phase steel (1.5mm) - nailed-joint is subjected to shear-tensile and cross-tension tests and numerical results are compared to experiments.

JOINING ALUMINIUM AND STEEL LAYERS

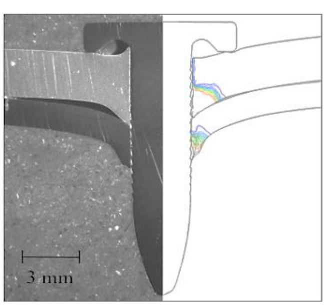

FIGURE 1: Experimental (Left) vs Numerical (Right) nailed-joint

In this paper, the joining configuration of interest is composed of a 1.5 mm-thick dual-phase steel sheet (DP780) and a 2.5 mm-thick cast aluminium ingot (AlSi10MnMgT6) (see Fig.1). We have chosen to focus our study on the following superposition, where aluminium is put as upper layer and steel as the lower layer. This choice has been motivated by the fact that nail-joinability of two materials is improved if softer material is located as the upper layer. As consequences we have considered this configuration more likely to be found on multi-material structures than the inverse one. Joining have been performed at IRT M2P Laboratory (Metz) using a commercial setting device called RIVTAC®. Setting parameters such as Hold-down pressure and Joining pressure have been respectively set to 1 bar and 5 bars. Beside experimental nailings, a 3D finite element model of the joining process has been built with FORGE® software – as presented in [5] - and run with the appropriate set of loading and boundary conditions to obtain at the final state, a nail fully seated into the metal sheets. Models have been validated on the considerations of piston displacement curve, sheets reaction across time and final joint geometry. Two damage formulations have been used to model sheets fracture in the nail penetration stage: a Lemaitre coupled approach (LEM) and an Extended Johnson-Cook coupled approach (EJC). Consequently damage grows differently into the sheets according to the formulation used. In addition to this effect, damage accumulation can be artificially boosted when the critical damage parameter[1] is changed. Moving up this value enables an extended damage accumulation before global failure happens. Moving it down triggers crack occurrence at lower damage value than before. Thus nailed-joint configurations which are taken as inputs of the testing simulations are the following:

(1) Lemaitre damage formulation (Critical damage parameter D_c* = 1)
(2) Lemaitre damage formulation (Critical damage parameter D_c* = 1,15)
(3) Lemaitre damage formulation (Critical damage parameter D_c* = 1,25)
(4) Extended Johnson-Cook damage formulation (Critical damage parameter D_c* = 1)

NAILED-JOINT MECHANICAL TESTING

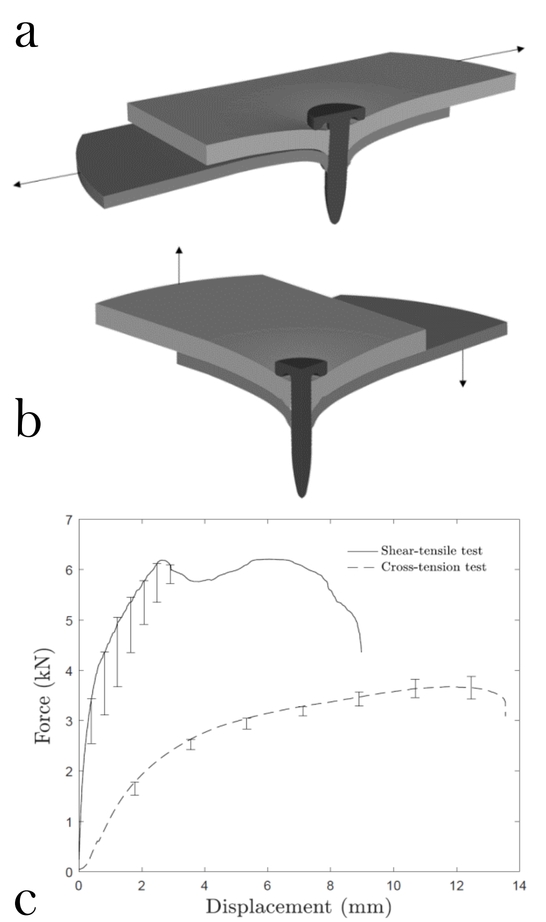

FIGURE 2: Cast al.(2.5mm)/DP780(1.5mm) nailed-joint
(a) Model for Shear-tensile test
(b) Model for Cross-tension test
(c) Experimental results of Shear and Cross-tension tests

Despite the development of plastic deformation-based processes such as clinching, riveting or self-piercing riveting (SPR), joint mechanical testing has to follow standards established for spots weld. Sample dimensions used in the present work (38 mm x 125 mm) as well as testing methodology are taken from standards [6], [7]. Two tests are commonly used to quantify the joint strength in the two main loading directions: Shear tensile test (see Fig.2 (a)) when load is perpendicular to the joint location and Cross-tension test (see Fig.2 (b)) when load is collinear to it. Assuming that joint strength of any intermediate loading direction can be decomposed into a Shear and a Tensile component, the joint qualification is usually limited to these two mechanical tests.

Experimental tests

Two nailed-joints processed in shear-tensile configuration and fourteen nailed-joints processed in cross-tension configuration have been tested at 10 mm/min. Both shear-tensile and cross-tension experimental curve are presented on Fig.2 (c) with only one curve each and associated to an errorbar to state for discrepancies between tests. Cross-tension tests are numerous because joint used to be weaker in this loading direction. Indeed in this particular case involving cast aluminium, the cross-tension strength is limited by material's ductility. Cohesion at the {Nail-Sheet} interface is so strong that a crack promoted in the upper-sheet, close to the nail, travels to the border until full joint failure happens. When nailed-joint is subjected to a shear-tensile test, load-carrying capability is limited by nail's material behavior. While nail shaft is moved downward, nail's head is stuck on the upper layer. Consequently, after an approximate displacement of 3 mm, nail shaft has been twisted enough to spread a crack at the {Nail head-Nail shaft} junction and trigger global fracture.

[1] Critical damage parameter, usually written D_c, is obtained from simulation, at the very last increment before crack can be noticed. For conveniency we use here a normalized critical damage parameter $D_c^* = D_c^{boosted} / D_c$ where $D_c^{boosted}$ is a user-defined parameter.

Numerical tests

Shear and Cross tensile configurations are modelled as presented in Fig.2 (a) and (b). Due to elements distortion at the {Lower sheet-Nail} interface, remeshing has been set every 10 increments for shear tensile simulations and every 20 increments for cross-tension ones. Time step is fixed to 2 s for cross-tension simulations and let free in the shear ones. As previously mentioned, four computational configurations have been taken as inputs of the nailed-joint testing simulations: three configurations of Lemaitre damage formulation (LEM) – the LEM 1.25 D_c* geometry can be seen on Fig.1 - and one with the Extended Johnson-Cook (EJC). At first, cross-tension and shear-tensile simulations were run on these models with respectively identical friction and numerical parameters to investigate how cumulated damage inside the sheets affects the nailed-joint response. Then friction effects are separately investigated on the cross-tension simulations.

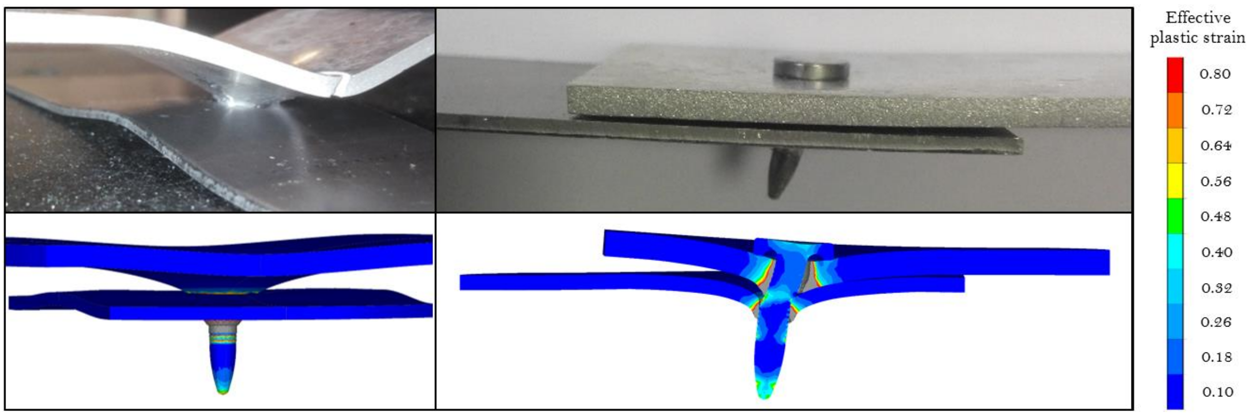

FIGURE 3: Experimental vs. Numerical nailed-joint final states in Cross-tension (*Left*) and Shear-tensile (*Right*) configurations

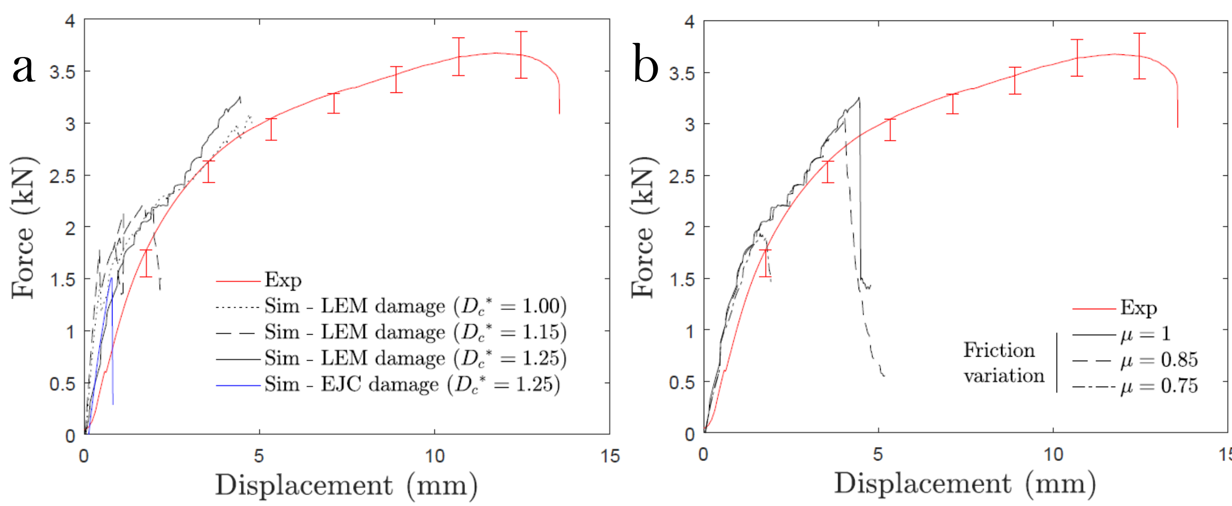

FIGURE 4: Comparisons between experimental and numerical Cross-tension tests conducted on Aluminium/Steel nailed-joint (a) Influence of damage formulation and critical damage value on the joint mechanical test (Same friction parameters) (b) Influence of friction parameters on the joint mechanical (using LEM 1.25 D_c* model)

RESULTS AND DISCUSSION

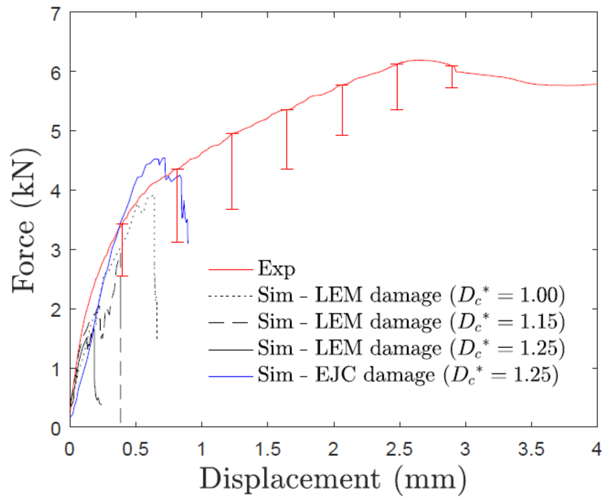

FIGURE 5: Comparisons between experimental and numerical Shear-tensile tests with different damage formulations and critical damage values on a Aluminium/Steel nailed-joint

As it can be noticed on Fig.3, simulations of testing configurations have caught global deformation modes noticed in the experiments: double-flexion in Cross-tension configuration and nail twisting in Shear-tensile configuration. Color scale - from blue to red - is used to picture the effective plastic strain amplitude inside the materials. Despite global agreement on simulations, several local discrepancies have to be mentioned: (1) cross-tension simulation cannot be run as far as in the experiment which implies that amplitude of sheets flexion is lower than expected. Thus crack formation and propagation in the upper sheet cannot be captured yet by simulations; (2) in shear-tensile test nail fracture happens close to the head whereas simulation seems to predict strain localization inside nail shaft, close to the lower-sheet area. Residual defects from nail forging process might be responsible of the nail head brittleness but cannot be modelled for the moment without accounting for damage inside nail's material. In terms of force-displacement curves, it can be noticed on Fig.4 (a) that computations of cross-tension models are in good agreement with experiment. Curve shape is satisfactory for LEM formulations but EJC's isn't because nail ridges got flattened during the nail insertion stage. Nail grip is reduced and after 1 mm curve suddenly falls. Results obtained from LEM formulations have each other given similar curve shapes. After an almost linear force increase, curves diverge at 2,25 kN and frictional contact between the nail and the lower-sheet is lost when force reaches 3,25 kN. In the best configuration, gap on the maximum experimental force amplitude is about 12%. As indicated in Fig.4 (b), friction effects plays a role in the nailed-joint mechanical response. When Coulomb parameter, notation μ, is decreased from 1 to 0,85 and then 0,75, it can be noticed that contact is lost earlier without a significant effect on the curve shape. The higher is the Coulomb-parameter value, the longer is the frictional contact maintained at the {Lower sheet-Nail} interface. Results from Shear-tensile simulations presented in Fig.5 show that all models responses follow a similar increasing slope but each one fails at a different displacement value. Shear-tensile resistance seems affected by the mechanical stress-state which results from joining simulations conducted with a particular damage formulation and critical damage parameter value. In addition to these parameters, several other parameters could influence nail rotation into the sheets and consequently load distribution into the nail: frictions, nail damages, numerical parameters…

CONCLUSION

In the present paper, a multi-material nailed-joint has been investigated in a superposition of a Cast aluminium layer (2.5mm) and a Dual-phase steel layer (1.5mm). Results of joining simulations run with Lemaitre and an Extended Johnson-Cook damage formulations have been used to build Cross-tension and shear-tensile nailed-joint simulations. Cross-tension maximum strength is highly affected by friction parameter at the {Lower sheet-Nail} interface. However damage formulation seems to have no significant effect of the curve shape: if geometry at the contact area is valid, friction will drive the whole structure in the nailed-joint reaction. Local differences in the damage values would not affect global reaction. In shear-tensile simulations as in the cross-tension ones, force-displacement curves follow the good trend but are stopped at a smaller displacement than in the experiment. Geometrical and contact issues at the interface have to be investigated in a further study to extend the frictional contact time and improve the predictions of permitted work dissipated into the joint until fracture happens.

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