IMPROVEMENT OF CRASH MODELS OF LARGE AERONAUTICAL STRUCTURES

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Abstract

The paper presents different new methodological developments in the field of the crash simulations of large aeronautical structures using explicit F.E. codes, such as RADIOSS. The main technical difficulties arise from the dimensions and the complexity of the structures to model (up to a complete aircraft) on the one hand, and from the complexity of the very local ruin phenomena (rupture of material or failure of riveted joints) on the other hand.

Two ways of improvement have been studied by ONERA in the frame of a DGA/SPAé French research program, and are presented in the paper. The first one deals with the development of simplified but realistic modelling methods, the main objective of which is to reduce the developing and the computing costs comparatively to a classical way.

The second one studies the dynamic behaviour of the riveted joints (experimentally and numerically), in order to improve their modelling in the crash models. The paper describes experimental characterisation techniques, for a single rivet (a new ARCAN test have been developed) then for a joint, and their exploitation to determine the parameters of numerical models.

In application, a crash model of the complete Airbus A320 have been built up by ONERA and Aerospatiale-Matra Airbus, making the simulation of different crash scenarios possible and realistic enough.

1 Introduction

The growing interest that the industry is paying to the study and the improvement of the crash behaviour of aircrafts leads to the arising of a number of new technical problems. To prepare to possible future certification rules, industrials have to prove their ability to numerically evaluate the crash survivability for complete aircraft. The dimensions and complexity of the considered structures are so big (thousands of pieces and thousands of riveted joints) that a number of simplifications must be undertaken to model the problem. But previous numerical and experimental studies have shown that some very local failure mechanisms might have a fundamental influence on the global crash behaviour of the aircraft. In particular, the figure 1 shows the result of a drop test of a section of A320 Airbus, which has been led at CEAT in July 1995, in the frame of the "Crashworthiness for commercial aircraft" European program. This picture shows the large damages in the lower part of the structure, which have been initiated by local ruptures of material or failures of riveted joints. Considering this point, the study of the joints dynamic failure is one of the major concerns of the industrials.

Figure 1 : Drop test of a section of A320 Airbus (CEAT, July 1995)

2 Simplified modelling methods

2.1 Objectives and industrial applications

According to the first field of research (simplification of complete aircraft models), a study has been carried out in co-operation with AEROSPATIALE-Matra, the objective of which is to build up a simplified, but complete and realistic enough F.E. model of the A320 Airbus, taking into account the aerodynamic loads, the actual masses and inertia, and an appropriate mesh in the parts where damage and highly non linear phenomena are expected to develop. ONERA-Lille was responsible for this last point. The F.E. model represents a 6 meter length rear part of fuselage. In a first step, the work was dedicated to the definition and validation of simplified approaches, the purpose of which is first to reduce the developing and computing costs but also to improve the confidence in the predictions made by these simplified models.

2.2 Description of the simplifying methods

The choice and the use of different simplifying methods rely on a preliminary analysis of the functional and mechanical role of the different pieces of the structure. Some of the characteristics may be modified in the areas where non linear behaviours such as rivet failures or plastic hinges are not likely to occur or, if ever they do, are of little influence on the global response [1]. Particularly, the modelling of some joints or of some geometries can be simplified.

2.2.1 Simplified modelling of joints

Due to the costs induced by the modelling of all the rivets (nearly two thousands for a single frame !), one of the main simplifying concept consists first in reducing the number of joints modelled. The joint links the different components altogether. It carries out the load through the structure. It also imposes contact between pieces. According to its position relatively to the deformations of the structure, it is possible to classify each rivet into two categories.

In the first one, the rivets do not risk to be broken or their possible failure does not influence the global behaviour. It is then possible to cancel in the model its capacity to break. If it behave rigidly, it is no use modelling the contacts. The only role which must then be kept is the load carrying one. It can be done just by melting the jointed pieces in a remaining one of equivalent thickness. This kind of simplification is called sub-structuring method, which will be developed in a further paragraph.

On the contrary, if the failure of the joint completely changes the way the structure behaves, it is compulsory to preserve and to model all of its functions. In that case a non linear spring is used to model the rivet. In the code RADIOSS, its characteristics are entered for each loading mode (tension, shear, bending, or torsion). The simplifying method consists then in using kinematic condition to connect the rivet nodes to the connected pieces. The rivet nodes are then rigidly linked to the nearest shell elements of the pieces to assemble. Comparatively to a classical node-to-node connection, this new modelling has several advantages. First of all it simplifies the meshing process, which becomes independent of the rivet positions. Second it enables to obtain a coarser and more regular mesh.

Nevertheless, this method requires a specific calibration of the rivet behavioural model, due to the change of the nature of the rivet/mesh kinematic constrains. For instance the ultimate length for failure have to be increased comparatively to a classical modelling, in order to prevent the rivets to fail prematurely. The complete procedure of determination of the characteristics of the rivet model will be described in the third chapter of this paper.

2.2.2 Principe of duplicate geometries

The second simplifying method arises from the following observation : aircraft structures are constituted of a great number of pieces, some of them having very similar geometries. The mechanical function of those pieces are identical and their geometrical differences are only due to physical constraints (systems, wires, etc …).

Such kind of pieces (or part of the structure) could then be grouped by functional and geometrical families. Inside one family, one (or a little number) basic geometry is defined which enables to rebuild all the pieces using geometrical transformation such as translations, rotations or symmetries. In each family, only this basic geometry is kept into a new basic minimal CAD model. This geometry is meshed, and then the complete mesh can easily be rebuilt by geometrical transformations.

This method can be applied to single pieces, but sometimes also to complete parts of the structure. For example, in the central area of the plane where the airframe section is constant, when two frames are considered to be structurally very similar, it is then possible to duplicate a complete frame, without making too coarse an approximation.

When it could be applied, this method reduces the developing costs of the model. When several pieces can be approximated and rebuilt from a simplified single one, a preliminary work is necessary to modify the initial CAD model. But then, the meshing process is greatly simplified. Associated to the simplified modelling of the riveted joints, it also provides a regular mesh, and makes their size easier to control.

An example of piece simplified in duplicating geometries is given in the figures below. The initial geometry is shown in the figure 2-a.

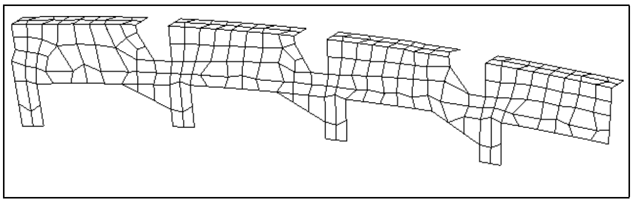

Figure 2-a : Continued piece meshed from the initial CAD model

The main mechanical function of this piece is to link the frame with the skin and the stringers. Its shape is constituted of a continuum of four quasi identical single geometries. It is considered that its mechanical role can be preserved without exactly respecting its true geometry. It makes then possible to keep and to simplify one single geometry in a new CAD model, to mesh it, and to generate the other pieces in duplicating the original one. The obtained set of pieces becomes then discontinued, as shown in the figure 2-b, but the main mechanical function is preserved :

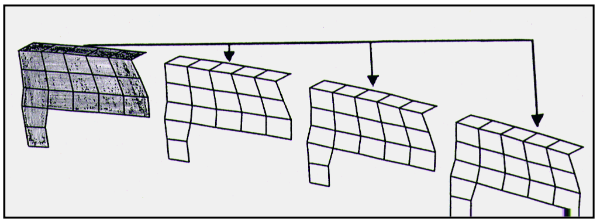

Figure 2-b : New pieces obtained by duplication of the mesh of a single simple piece

2.2.3 Sub-structuring method

This method consists in getting rid of the modelling of joints which have no risk of failure or the failure of which has little influence on the global response. The different jointed pieces can then be melt in a remaining equivalent one, the thickness of which being computed as the sum of the thicknesses of the different initial pieces.

New “sub-components” are then created in the CAD model by translating the initial objects in one reference plane and reshaping the geometries. Simplified footprints of the projected objects are preserved in order to take them into account for the meshing and the attribution of element equivalent thicknesses.

The developing costs include the construction of a new specific CAD model. If a initial CAD model of the structure already exists, its modifications in the areas where the sub-structuring method is applied can require a relatively significant work. If a new CAD model has to be built up, the new arrangement of the geometries can be taken into account from the beginning of the process, and the developing cost of the CAD model is then approximately the same as in a classical way. In both cases, the following meshing process is greatly simplified.

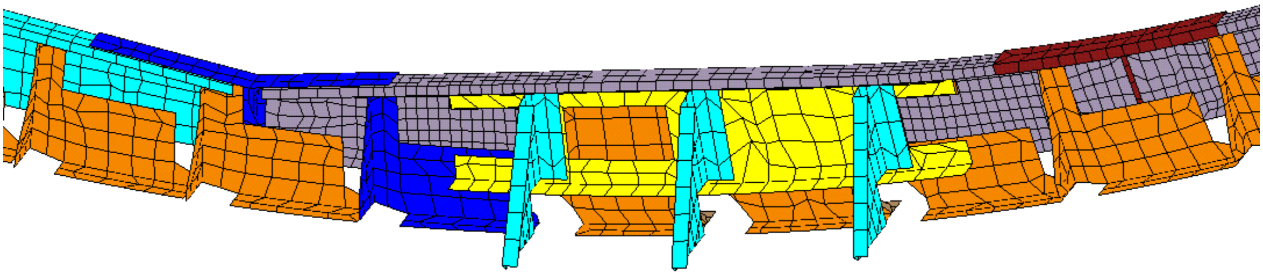

Figure 3-a : Frame section meshed from real geometries of initial CAD

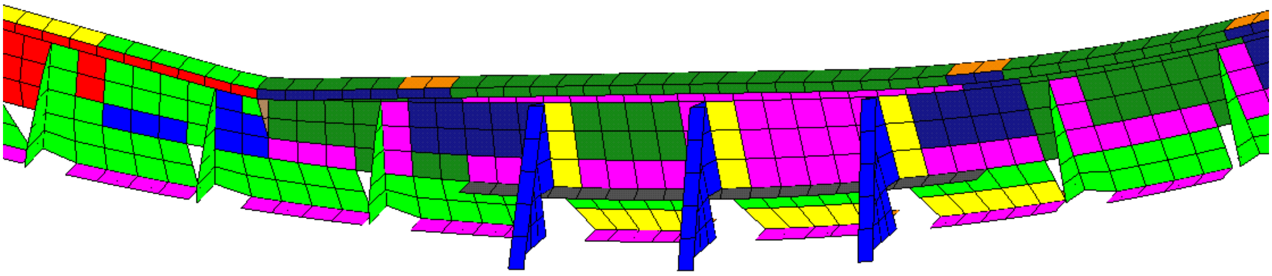

Figure 3-b : Simplified mesh of the same frame section with melted geometries

Comparatively to a classical modelling, the application of the sub-structuring method leads to greatly reduce the computing costs. Indeed, the number of elements can be greatly reduced, and contact interfaces and rivets can be suppressed. For example, this method led to a 67% reduction CPU cost factor for a single frame model.

An example of application of the sub-structuring method to a frame section is given in the figures above. A classical model meshed from the real geometries of the initial CAD model is shown in reference in the figure 3-a. In some areas, three different pieces are riveted together. The modelling of all the rivets, directly connected to the nodes of the mesh, induces an increase of the number of elements and makes the mesh irregular in this areas. The same part of the structure, modelled in using the sub-structuring method, is shown in the figure 3-b. Because of the little risk to observe a complete joint failure in this area, all the original pieces have been melted together. Each colour on the figure represents a particular thickness. The allocation of all the local equivalent thicknesses during the meshing process requires a careful work. The main progresses are the large reduction of the number of elements, the improvement of the regularity of the mesh size, and the non-modelling of the rivets and contacts. The resulting computing costs are then greatly decreased comparatively to a classical approach, and the validity of the results are preserved.

2.3 Validation of the simplifying methods

After having tested and validated separately each type of simplification, the final validation of the simplified modelling methods has been carried out in comparing the results of two crash simulations of the same large aeronautical structure. This one has been modelled in a classical way in the one hand, and using a mix of the new simplified methods in the other hand. The structure modelled is a 6 frame part of A320 Airbus. The “classical” model has been provided by Aerospatiale-Matra Airbus. The real geometries has been respected, all the rivets are modelled, and the meshes are relatively fine. It is composed of about 180000 shell elements, and the initial time step (mesh size dependent) is about 10^{-3} ms. The model to be validated has been built up by ONERA-Lille following simplified modelling methods, only applied to the lower part, where non-linearities have a great influence on the global behavior of the structure. This model is composed of only 80000 shell elements, and its initial time step has been increased up to 1.3 10^{-3} ms. Both factors have been led to divide the computation costs by three comparatively to the "classical" model.

In order to validate the approach, two kinds of correlations are sought. The qualitative one concerns the location of the non-linear mechanisms (plastic hinges, buckling) and the chronology of the main ruin phenomena. The qualitative one concerns the level of the impact force on the ground, and of the energy absorbed by the structure.

Concerning the qualitative analysis, the figures 4-a and 4-b shows the main plastic hinges for both models, which are located on the frames and play an important role in the energy absorption. We can observe that the location and the shape of the plastic hinges is very similar for both models.

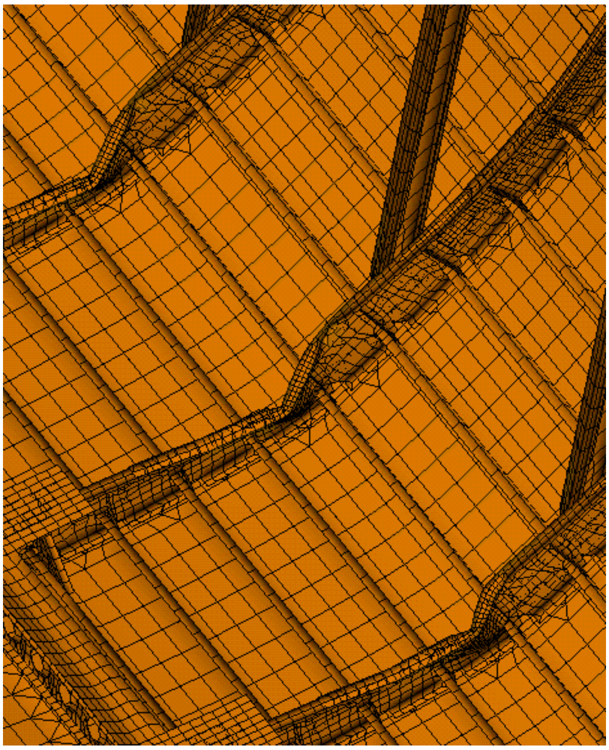

Figure 4-a : Plastic hinges – "classical" model

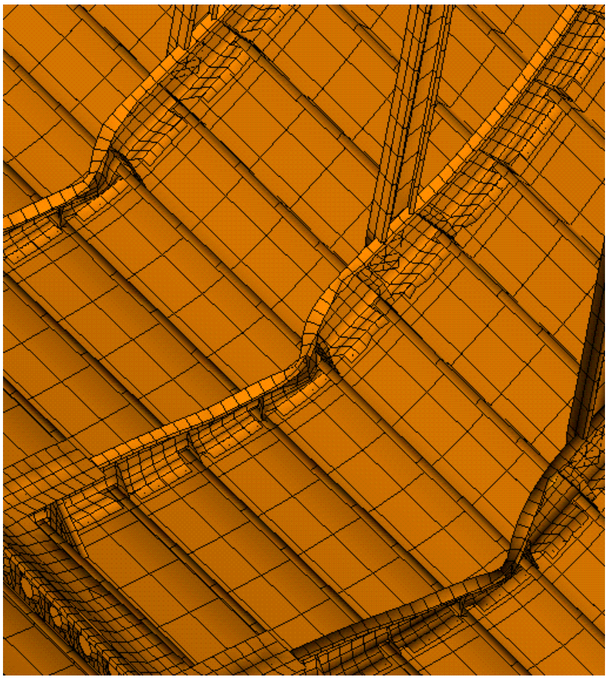

Figure 4-b : Plastic hinges – "simplified" model

The validation of the simplified modelling methods is confirmed when comparing both impact forces on the ground versus time curves (see figure 5). Their level and their evolution look very similar.

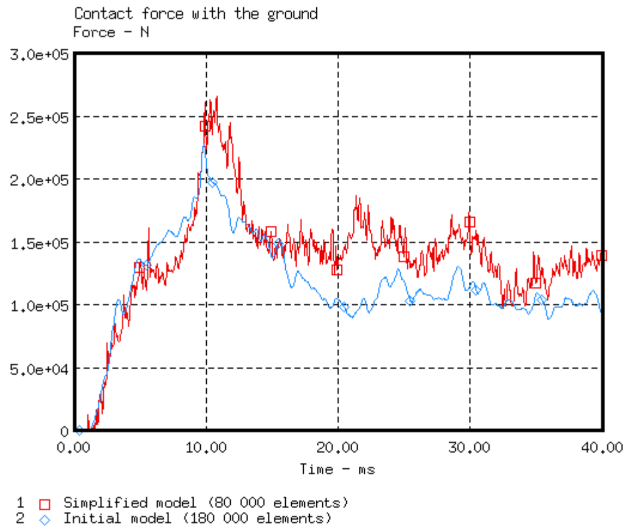

Figure 5 : Comparison of the impact force

2.4 Application to the complete aircraft

Once the simplified modelling methods developed and validated, the next step has been to perform the simulation of a complete commercial aircraft (an A321 Airbus), in the frame of a co-operation between Aerospatiale-Matra Airbus and ONERA. Concerning the ONERA task, the new modelling methods have been applied to the real rear part of the aircraft, sited around the first impact area, where damages and non linear phenomena are expected to develop.

The main interests of this work have been to prove the technical capability to perform a representative crash simulation of a complete aircraft, and to quantify the developing costs of the model in an industrial context.

The structure modelled by ONERA is a six meters length airframe. Its non cylindrical geometry (non constant section in the rear part) cancels the possibility to duplicate a complete frame. So each frame has been individually modelled. The sub-structuring method has been largely applied. Concerning the developing costs, the application of the new modelling methods has slightly increased the CAD works, but simplified the meshing process, while improving the control of the size and the regularity of the mesh, so the confidence in the simulation results. The obtained model is shown in figure 6. It is composed of about 75000 shell elements and more than 5000 rivets elements.

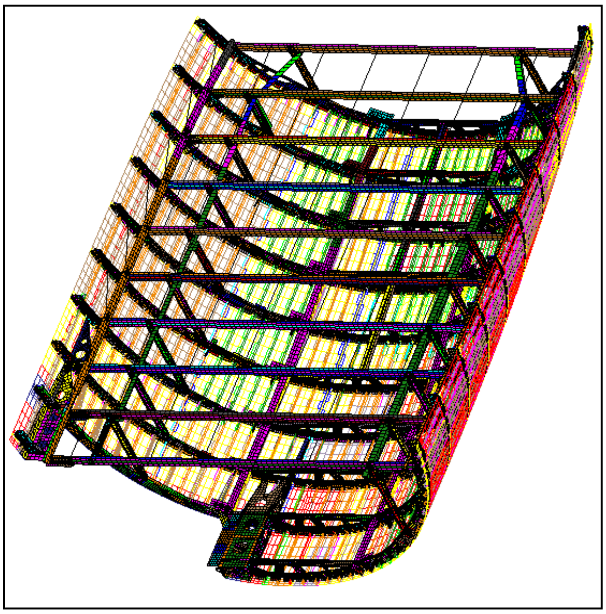

Figure 6 : Mesh of the rear part, sited around the real impact area

The rest of the aircraft have been modelled by Aerospatiale-Matra Airbus, following a different approach. Its mesh can be much coarser than in the impact area, due to its linear behaviour. The real mass distribution is respected, and an aerodynamic load is applied, varying with the angle of incidence of the aircraft and taking into account the ground effect. Finally, the obtained model is composed of almost 200 000 finite elements. This model is shown in the figure 7.

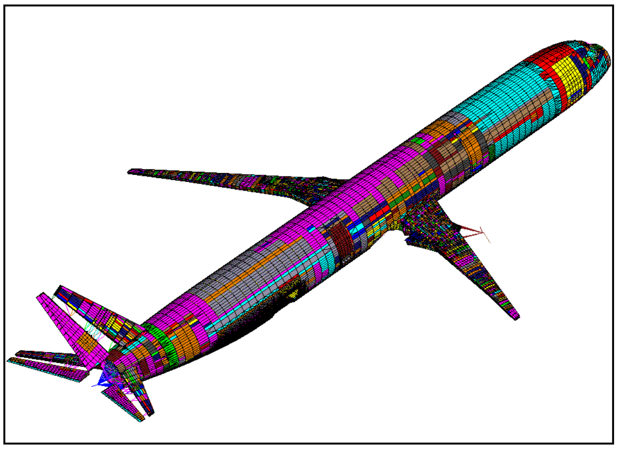

Figure 7 : Model of the complete A321 Airbus well suited for crash studies

The first crash simulations have been recently performed by Aerospatiale-Matra Airbus with this model. The CPU time of a complete crash simulation (after stalling) is about 10 days on a bi-processor SGI R10000 workstation. This time is highly dependant of the used platform, and the constant increase of the computer's performances will shortly make this simulations usable in industrial design process.

Further to this first success, the co-operation between ONERA and Aerospatiale-Matra Airbus will be continued, and new perspectives are already planed. The first one is to refine the mesh in the front part of the aircraft model, in order to improve the accuracy of the model after the stalling. The study of other impact configurations will also be led, such as ditching simulations.

3 Modelling of riveted joints

3.1 Introduction

Concerning the specific study of the riveted joints modelling, other basic or applied studies are performed in parallel in order to answer questions from the industrials and to improve the capability of taking into account the right joint failure mechanisms in crash simulations. One of the main difficulties is due to the fact that classical characterisation techniques can not provide directly the behaviour law of a numerical 'rivet' element. In particular, the structural embrittlement resulting from the riveting process and from the stress concentration around the rivet hole (not modelled) have to be taken into account. On the other hand, the loading transmitted from the pieces to the rivet depends on numerical parameters, such as the mesh size or the links between the rivet ends and the mesh of the pieces to be connected. Different ONERA works [2, 3] have led to develop a complete procedure in order to determine the characteristics of appropriate rivet models. This methodology includes four consecutive steps [4], which are developed in the next paragraphs.

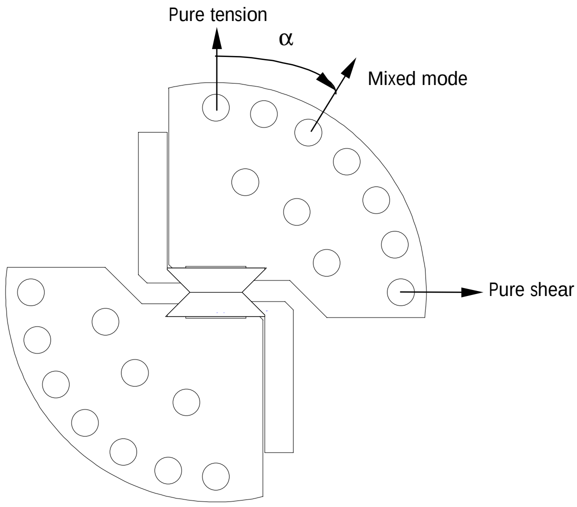

Figure 8-a : ARCAN set-up for the rivet characterisation

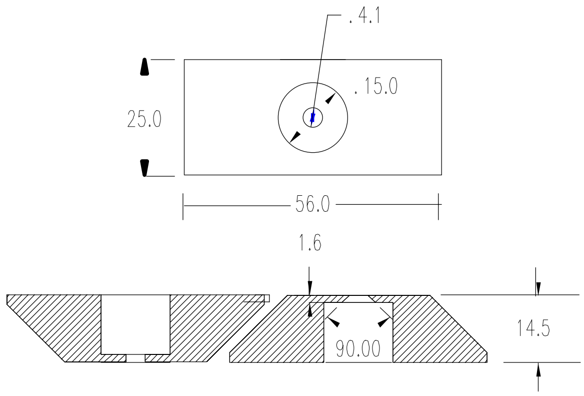

Figure 8-b : Specimen

3.2 Characterisation of a single rivet

The first task concerns the characterisation of the rivet itself. A new experimental technique to characterise rivet strengths and failure mechanisms under dynamic multiaxial loadings are investigated (ARCAN test procedure). Applied to the rivet characterisation, this experimental set-up make a perfect control of the loading mode (tension, shear, and mixed) possible.

The experimental ARCAN set-up is shown in figures 8-a and 8-b. Both steel disk quarters orient the load, and both hardening steel heels (linking the experimental set-up to the rivet) the rivet itself. The tests are led up to the rivet failure, and provide load versus displacement curves for each tested load direction. The dynamic influence can also be studied.

Due to the variety of the different types of rivets, the experimental campaign would become relatively expensive. In order to limit the experimental costs, a numerical characterisation technique based on accurate finite element modelling has also been developed [3], which is not presented in this paper.

3.3 Characterisation of a riveted joint

The second step concerns the determination of the reference behaviour of an elementary riveted joint. The characterisation method presented in this paper is led following an experimental way, but a numerical approach has also been developed and validated [3].

For this characterisation, shear single lap riveted joint elementary specimens are used, which are constituted of two aluminium alloy plates linked by a single rivet located in the middle of the overlap area. The dimensions of the plates (in particular the edge margin) are defined for mechanical strength from calculation rules which avoid boundary effects to influence the joint behaviour. An example of specimen is presented in the figure 9.

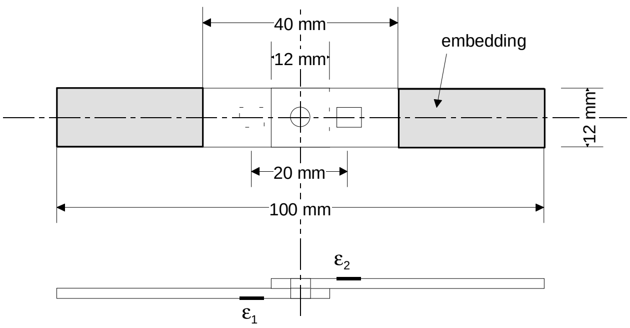

Figure 9 : Shear single lap riveted elementary specimen

The test consists in loading the riveted specimen in tension, the rivet working initially mainly in shear. After the first linear phase, the joint behaviour become notably more complex. Plasticity appears in the plates (with a more or less large hole ovalization) and in the rivet body. Finally, the joint fails following different modes (shear or pull-out rivet failure, or plates cracking), depending on the type of riveted joint (materials and geometries). Two examples of specimens after test are shown in the figures 10-a and 10-b, with very different failure modes.

Figure 10-a : Single lap riveted specimens (with aluminium type LN 9198 rivet) after test

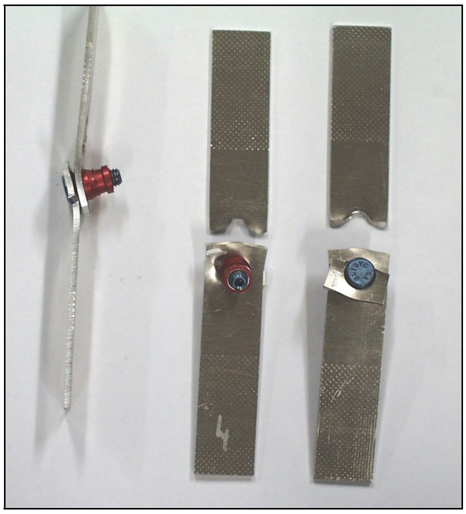

Figure 10-b : Single lap riveted specimens (with titanium type DAN 563 rivet) after test

During each test, the load versus displacement curve is recorded, in order to provide reference response for further numerical developments.

3.4 Determination of a reference joint model

This third step aims to define, for each type of joint appearing in the structure to be modelled, the reference parameters of the numerical joint model. The objective is to obtain a good agreement with a reference response in modelling the riveted joint coarsely enough to be compatible with a complete structure modelling (in particular in avoiding volumic elements). The main difficulty is to introduce in the model the local embrittlement of the plates. The parameters to be defined are mainly the mesh size of the plates, and the local stiffnesses (thicknesses, material law).

In order to determine the model parameters, the tests on elementary riveted joints, described in the previous paragraph, are simulated with the RADIOSS code. The plates are modelled with shell elements. The rivet is modelled by a single “beam-spring” element, with non linear behaviour laws in tension and in shear, which arise from the test results performed on the single rivets (see paragraph 3.2).

The objective of this step is to obtain the best correlation between the numerical load versus displacement curve and the reference one. The characteristics of the rivet element are kept unchanged along the process. The geometrical parameter is the mesh size of the plates. The other parameters represent the effects of the embrittlement, that can be introduced in locally reducing the plates thicknesses and/or in softening the material law (in particular in modifying the breaking point) in a more or less large area sited around the rivets. In the future, a new "embrittled" shell element, still in progress at ONERA-Lille [5], would take this effect into account directly. Once a good agreement with the reference response obtained, the parameters of the joint model are considered to become references for structural simulations.

3.5 Adaptation to simplified models

The last step aims at adapting the characteristics of the riveted joints models, obtained at the previous step, to the global modelling methods, applied to the crash simulation of complete aircraft (presented in the second chapter of this paper).

At first, the main families of subsets constituted of riveted pieces are selected in the complete structure to be modelled. Their geometries are then separated from the rest of the structure and finely modelled in using in the riveted areas the parameters defined at the previous step. An example of such modelling is given in the figure 11 for one of the selected subsets. The colour differences around each rivet represent specific thicknesses and material laws, in order to locally embrittle the structure. A loading, representative enough of a real one, is applied until the complete joint failure and a reference response (load versus displacement curve) is obtained that way.

In order to adapt the rivet modelling to the complete aircraft model, the same subsets are then modelled following simplified methods, with much coarser mesh and without any local embrittlement. Such a model is shown in figure 12.

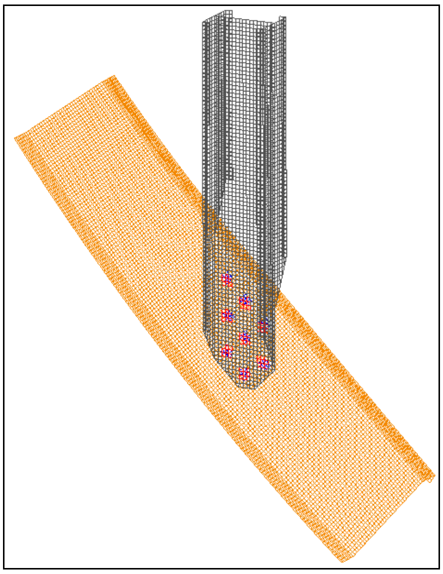

Figure 11 : Reference subset model for the reference response

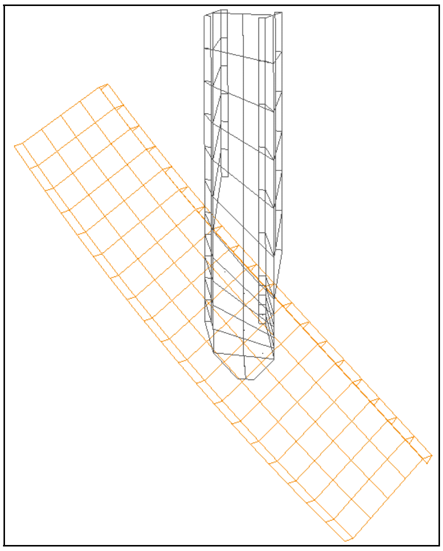

Figure 12 : Subset modelled following simplified modelling methods (with rivets to be calibrated)

The same load as previously, applied on the simplified model with the initial rivet models, leads to overestimate the load and to obtain premature joint failure. This wrong behaviour is mainly due to the fact that the mesh is not fine enough to represent very local plastifications and deformation modes, and that the embrittlement is not taken into account.

In order to correlate the reference response, those local effects, not finely enough represented in the materials, are introduced in the characteristics of the rivet element itself, which have to be calibrated. The rivet element behaviour laws in tension and in shear are then modified in their linear and non linear parts, such as the breaking points, until obtaining a good agreement with the reference global response. Recent applications [4] have proved that a such calibration could give very good results in terms of load level such as of the chronology of rivet failures. An example is given in figure 13.

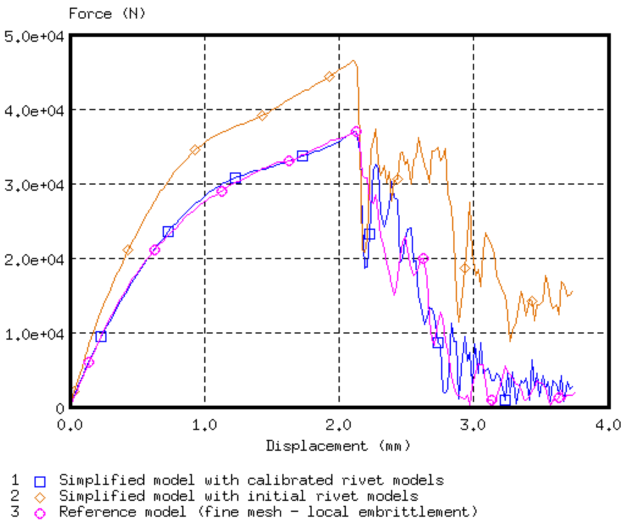

Figure 13 : Comparison of the different force versus displacement global subset responses

The calibrated rivet models may then be introduced in the complete aircraft model, in order to improve the accuracy of the complete structure simulation results.

4 Conclusion

Different ways of progress, recently performed by ONERA-Lille in the field of the development of full aircraft crash simulation models, have been presented in this paper. This works rely on experimental as well as numerical studies. In particular, concerning the problem of the riveted joints modelling, the development of new experimental devices and methodology has made possible significant improvements in the accuracy of the prediction of structural ruin events.

Today, a first realistic crash simulation of a full aircraft has been performed in co-operation with Aerospatiale-Matra Airbus. In the future, this model may integrate new developments, and other impact configurations (such as water impact, …) may be simulated.

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