Proceedings of the 7th International Conference on Mechanics and Materials in Design
Albufeira/Portugal 11-15 June 2017. Editors J.F. Silva Gomes and S.A. Meguid.
Publ. INEGI/FEUP (2017)

PAPER REF: 6568

EVALUATION OF A FE MODEL FOR THE MECHANICAL ANALYSIS OF A COMPLEX THIN-WALL CFRP STRUCTURE

J.C. Riol, E. Casarejos(*), A. Segade, P. Izquierdo, J.L. LópezCampos, P. Yañez, J.A. Vilán
Department of Mechanical Engineering, University of Vigo, E-36310 Spain
(*)*Email:* e.casarejos@uvigo.es

ABSTRACT
In the paper we describe the results obtained with finite element models to describe a CFRP thin-wall honeycomb-like structure. We present our strategy to use models capable of producing reliable and robust results compared with reference tests. Our aim was to build a framework to allow for an effective design and calculation interplay.

Keywords: composite, CFRP, thin-wall, finite element model.

INTRODUCTION

An ideal sensor or detector for particles or radiation would have a maximal active volume free of structural parts, which additionally may induce sided effects. For many applications, light structures are demanded together with the condition for providing with a robust and safe mechanical frame and, usually, a tight positioning of critical elements. Honeycomb-like structures using thin-wall parts can provide excellent solutions. The application of reinforced plastics typically with carbon fibres (CFRPs) may be an extra option, providing large strength to mass ratios. Examples can be found in new generation telescopes, spatial applications and physics laboratories all over the world.

One particular case is the detector CALorimeter for the In Flight detection of gamma-rays and light charged pArticles (CALIFA) developed for one of the flagship experiments of the international facility FAIR (Germany). The CALIFA system is currently under R&D (Califa, 2014), involving more than 50 different institutes and several hundreds of collaborators.

A CASE REFERENCE: THE CALIFA DETECTOR

The detector CALIFA will surround the reaction centre in many different types of experiments. The active sensor parts are prismatic scintillator crystals coupled to opto-electronic devices. It is necessary certain segmentation into individual sensors, and the crystal shapes and lengths (up to 220 mm) must vary according their position in respect to the centre. The mechanical support is a honeycomb structure to hold about 2000 crystals inside, and conform the shape around the centre, while the positioning of the crystals must be ensured by the structural stiffness. Indeed, the walls must be as thin as possible; therefore CFRP woven pre-preg was used for the construction. The CF-structure was built with more than 500 CFRP thin-wall (0.3 mm) parts, distributed in sixteen rings, each ring laid on each other's side in a conical envelope, see Figure 1.

The inner diameter is 600 mm, the outer envelope 1060 mm and the length is 990 mm. It holds about 1300 Kg of crystals, achieving a ratio of 0.7 % for the CFRP weight to total mass (Casarejos, 2014).

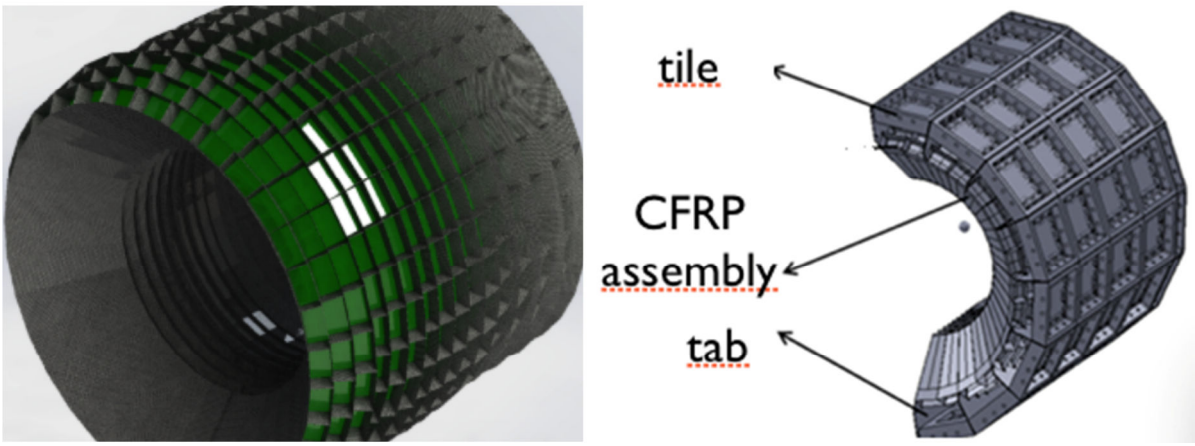

Fig. 1 - Drawing of the honeycomb CFRP structure (left), formed by 16 rings. Almost 2000 prismatic sensors surround the reaction target and are hold inside the structure. The CFRP structure is placed inside a cover (right) built with the individual parts (tile) and hold by the tab parts.

The sensors required a light-tight and gas-tight enclosure. A cylindrical cover was the natural shape solution. The cover was designed with 64 similar parts (tile) assembled in a regular segmentation, see Figure 1. The outer diameter of the cover is 1200 mm. The cover is a very stiff and robust assembly, and allows for the right emplacement by a gantry or equivalent external structure in the lab.

The parts that hold the CF-structure and connect with the cover are critical components of the design. Those parts (tab) are thin plates with flaps at one side. A pair of tabs can grab within the flaps the wall (a fraction) of a CFRP part. The tabs are fastened in between tiles, and the closing of the cover provides the support of the CF-structure, see Figure 1.

For the correct sensor positioning it is critical to evaluate the deformations expected in the structure. Therefore, the design can be made stiff where necessary, and fine adjustments be included at the external structure to rightly adjust the position.

VALIDATION OF A FE MODEL WITH CFRPs

The capabilities of the Finite Element models for evaluating CFRP materials are always limited. Despite the integration of specific CFRP pre-processors in software packages, the description of the orthotropic materials is difficult because the limitations of the micro-mechanical models, and the scarce data available for many fabrics in the market.

The assembly of the CF-structure contains 500 parts of CFRP to be defined wall by wall, because the orientation of fibre, and the tabs and tiles. There are thousands of joints between the tabs and the CF-structure, tab to tab, tab to tile, etc., and they include bolts and friction contacts. Any FE calculation becomes largely time consuming for both the definition of the model as well as the resolution time. Indeed the convergence can be problematic due to the big set of non-linear frictional joints. In order to make an efficient design framework for the CALIFA project, we wanted to provide an effective and realistic FE model, while reducing as much as possible its complexity for both the definition and the calculation.

We studied a group of models with different assumptions, and were crosschecked with reference data. The data was obtained with a simple and robust setup capable to provide values to compare straightforward and to evaluate the model results.

Setup and measurements

We performed a collection of mechanical tests in a simple and robust setup. Two CF-parts were grabbed together and hold by tabs at each side; the flaps of the tabs were clamped by a pair of bolts and nuts passing through. The tabs, 2 mm thick plates of steel AISI-316L, were also fasten to one tile and a block bearing. This mounting was essentially the same as that designed for the whole detector. See Figure 2 the description of the assemblie. We used the most unfavourable direction that the structure could stand (horizontal), maximizing the deflection at the edges of the parts. Dial gauges (0.005 mm resolution) were firmly located at several points far away from the bearings, in the horizontal plane.

A quasi-punctual load was applied with a finger-like stick. The maximum load we could apply without compromising the integrity of the walls was 13.5 N. We check that the displacement measured was linearly dependent with the load values within that range. A second load measurement was done by introducing steel blocks inside the parts. The shape, weight and centre of mass of those blocks were equal to the actual active crystals (about 2.5 kg per part).

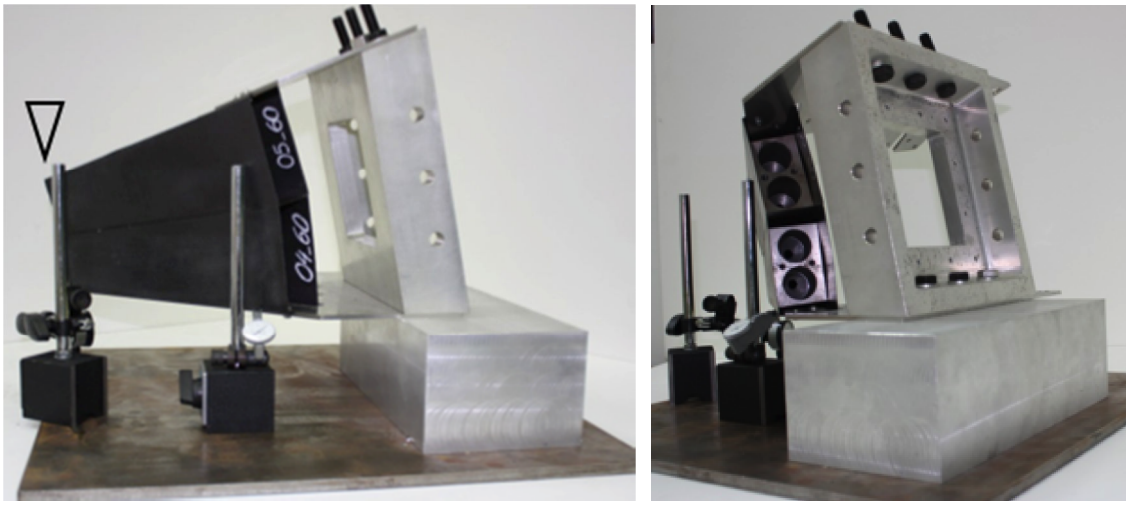

Fig. 2 - Pictures of the setup mounted with two CF-parts. Left: The setup was located so that the lower walls of the CF-parts were in the horizontal plane. Two tabs at each side grab the CF-parts walls in between. The tabs were bolted to the tile and fixed to the bearing block. Two dial gauges were firmly located about the horizontal plane: at the far corner of the CF-part, and at the edge of the lower tab. The triangle locates the point where the point-like load was applied. Right: another view of the setup. The blocks used to load the parts are visible.

Finite Element model

All numerical calculations and finite element models were done with ANSYS®. The most detailed description for modelling CFRPs was implemented with the ACP pre-processor, able to combine these materials together with isotropic materials into complex models.

Material properties

We used typical values found in literature for the metallic parts (aluminium 5083 and steel AISI-316L).

The CFRP materials required the characterisation of many details of the fabric. We used an epoxy-CFRP fabric pre-preg 1K plain-weave, 0.15 mm thick, with a resin content of 40% (weight). We also paid attention to the fiber orientation in each of the faces. In a detailed search we found no data corresponding to this particular fabric. Neither the producer could provide it. (Chretien, 2002) developed a model for plain fabrics, which resulted successful in the description of 1K fabrics. It solved the limitations found, e.g., in (Naik, 1995) and included the properties in the out-of-plane direction. The properties we used to define our fabric are listed in Table 1. For the pre-processor, also the fabric woven type, thickness, and the orientation of the fibres in each face as input.

The characterization of the orthotropic properties of all the parts with the pre-processor is largely time consuming for both the definition and the calculation. Considering the behaviour observed in some of the partial models we built, we made models considering the CFRP as an isotropic material. The properties of this option were defined with the same (maximum) tensile modulus (57,98 GPa), a generic Poisson ratio (0.3), and the corresponding shear modulus (22,30 GPa). These values provided a model with a behaviour close to the one measured.

Table 1. Mechanical values used to define the CFRP pre-preg used.

Density $[g/cm^3]$	E_x $[GPa]$	E_y $[GPa]$	E_z $[GPa]$	G_{xy} $[GPa]$	G_{yz} $[GPa]$	G_{xz} $[GPa]$	ν_{xy}	ν_{yz}	ν_{xz}
14,8	57,982	57,982	12,056	41,823	38,145	38,145	0.050	0,439	0,439

Mesh model

In order to optimize the resources, the models included a finer mesh only for the CF-parts. This was done consistently according the relative difference of deformation and rigidity of the materials. The mesh of the aluminium tiles was done with 15 mm tetrahedral elements, and at least three nodes in the part thickness. The mesh had about 13500 elements. For the steel tabs we used 5 mm hexahedral elements, defined as coherent for both sides. The number of elements was about 4500.

For the CF-parts we used meshes with 3, 2 and 1 mm hexahedral elements. We found that 2 mm provided a stable result, and a reasonable calculation time. The typical number of elements for CF-parts was about 69000. Some details will be show in the next sections.

Contact model

The study of the contacts was also a key for simplifying our model. We implemented changes to relax the contact definitions, while keeping the behaviour of the model performance. For the bolted parts we used the pressure-cone method (Ito, 1977) with a cone angle of 45 degrees (Shigley, 1989). We studied models with and without frictional contacts. We found in the results that this contact added tinny extra rigidity to the system and affected negligibly to the

total deflection. Therefore we preferred linear conditions instead, and included a restriction of surface no-separation (also linear type) where possible.

The contact between two CF-parts was defined as bonded, since they were actually glued together.

The contact between tab and CF walls was defined as bonded in the pressure cone, and the rest with a no-separation restriction. The same condition was kept for the tab-tab contact. Therefore we restricted out-of-plane displacements, while bending was allowed.

The contact between tab and tile was defined as bonded, extending the condition beyond the pressure cone, due to the strong friction expected at that tightly fasten region.

Loads and boundary conditions
The model conditions reproduced as much as possible the test conditions. A strip region of the tab in contact with the bearing block, 20 mm width, was defined as fixed. The point-like loads were applied in value, direction and location corresponding as close as possible to the test condition. In the cases with part-filling blocks, their own weight was acting as load.

Model results

In Table 2 we show the results obtained in some of the models we studied, as well as the measured data. It is worth to note that we kept the measurements to a minimum number of robust reference points. More details as edges, contours, shapes, etc. would have caused more difficulties to discuss that sharp information to select the more appropriate models.

Model A corresponds to the use of the pre-processor for CFRP and frictional (non-linear) contacts in most of surfaces. The load applied was punctual-like. The agreement observed in both points is excellent in the corner (1% relative difference) and within the measurement uncertainty (0.020 mm) at the flap. This result confirms that both the FE model definition, including mesh and contacts, as well as the material characterization were reliable and provided robust results for the further discussion.

In model B we implemented the CFRP material re-definition, and the linearization of the contacts. We studied other intermediary cases to search for isolate individual effects, but we describe here only the significant states. In this model, the values at the corner differ by 21%, still a rather good result and close to the measurement uncertainty. Indeed, the result at the flap is now very close to the measured value (below 2%, relative difference). The side-effects produced by the re-definition of the material is counterbalanced by the linearization of the contacts. The trade-off of effects of the combined approximations for material and contacts resulted positive to obtain the model which being simplified, kept the functional description.

Model C corresponds to the tests done with the blocks to load the structure. The results obtained are in a fairly good agreement: within 24% at the flap and 11% at the corner (relative differences).

Reviewing the results, we can see that in general terms one or another model can provide values always within the 25% relative value in respect to the measured data. This result is considered as good enough for the application to study the design in the terms need for the project, as we will discuss in the following.

Table 2 -Measured data and the results of the FE models proposed. Values in mm. Test P and B are for the point-like load and the load with blocks, respectively.

	test P	model A	model B	test B	model C
tab	0.060	0.050	0.066	0.265	0.330
corner	0.140	0.142	0.110	0.560	0.498

FE MODELS OF THE STRUCTURE WITH CFRPs

The successful description obtained with the model applied to the benchmark setup and data, allowed us to expand the model to bigger parts of the CFRP structure with confidence. Our first goal for the design project was to describe parts large enough with characteristics that resume properly the whole structure. On the one hand the structure is symmetrical in respect to the median plane that parts the structure in left-right sides (note that gravity works equally on both halves). On the other hand, we selected a segment and a ring as the most representative parts of the structure.

The 'ring' corresponded to the collection of 16 equal parts that form the 180-degree arc of one side of the structure. They corresponded to the most forward ring, where the parts are most tilted in the conical shape, and being in contact only on one side, see Figure 3. They were hold by 8 tiles and a collection of tabs to grab the set.

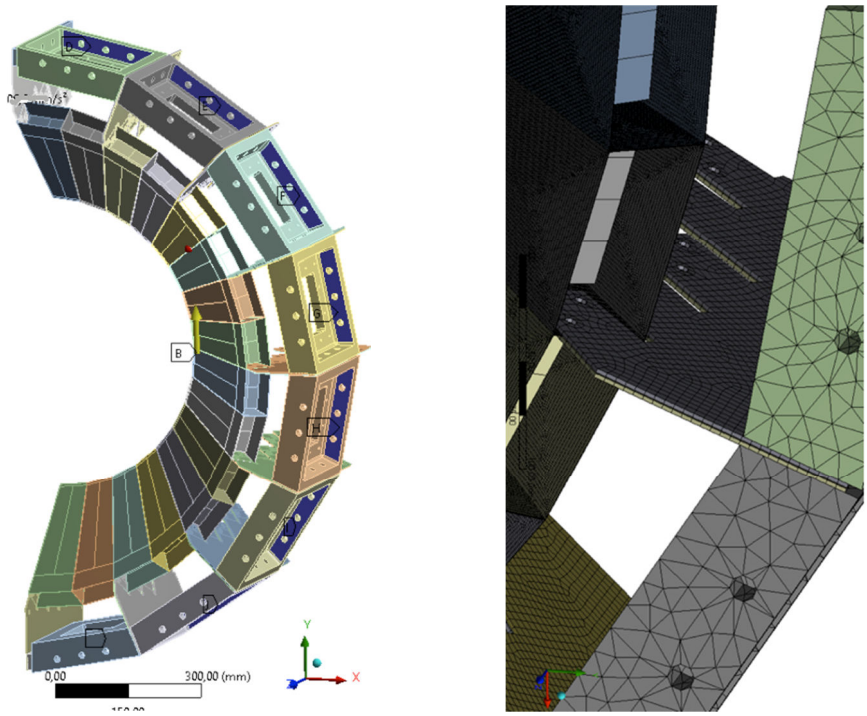

Fig. 3 - Drawing of the CAD model (left) used to define the 'ring' assembly. One line of 16 CFRP parts, in contact side-to-side formed a 180-degree vertical arc, supported by 8 tiles and tabs. The tiles were fixed as if placed by an external structure using some fixture at the dark locations. The mesh defined in the model (right): tiles: 15 mm tetrahedral elements; tabs: 5 mm hexahedral elements; CF-parts: 2 mm hexahedral elements.

The 'segment' corresponded to a collection of 32 parts, with 16 different types, disposed in a two-parts width and a row front-to-back, see Figure 4. They were hold by 5 tiles and the corresponding set of tabs.

The FE models for each setup were defined following the description obtained previously for the material, mesh and contacts. The loads where implemented as in the actual case, thus the weight acting as the natural force on each assembly. The tiles were supported as if they were fixed at an external support, see Figures 3 and 4 for details. The ring was studied in its natural vertical position. The segment was located in the most un-favourable case, being at the horizontal plane.

Both the ring and the segment were large extensions of the small model used as evaluation with two parts: 800% and 1600% factors respectively. We considered that studying these representative parts could provide more information for the detail of the behaviour that the whole structure as a single assembly. Also, it is possible to consider the construction of a test bench with those structures for partial crosscheck studies.

We selected as reference points those with the maximum deflection, therefore we took (mesh nodal) points at the edges of the CFRP parts, see Figures 5 and 6. The obtained results of the model for the two structures are shown in those plots.

The values amounted about 0.1 mm (0.12 mm maximum) in the ring structure; 0.2 mm (forward and middle locations) and 0.3 mm (backward location) for the segment structure. These values, as compared with those measured in the two-part setup, and considering the volumes we study now, are remarkably low. This is a confirmation of the large stiffness of the CFRP structure designed.

The values may lack reliability in terms of absolute values. The model showed deviations up to 24% in respect to the measured values for the small two-parts model. Moreover, the cumulated uncertainties in the large assemblies are tough to predict. However, even a 300% uncertainty underestimation would provide with values well below 1 mm deflection.

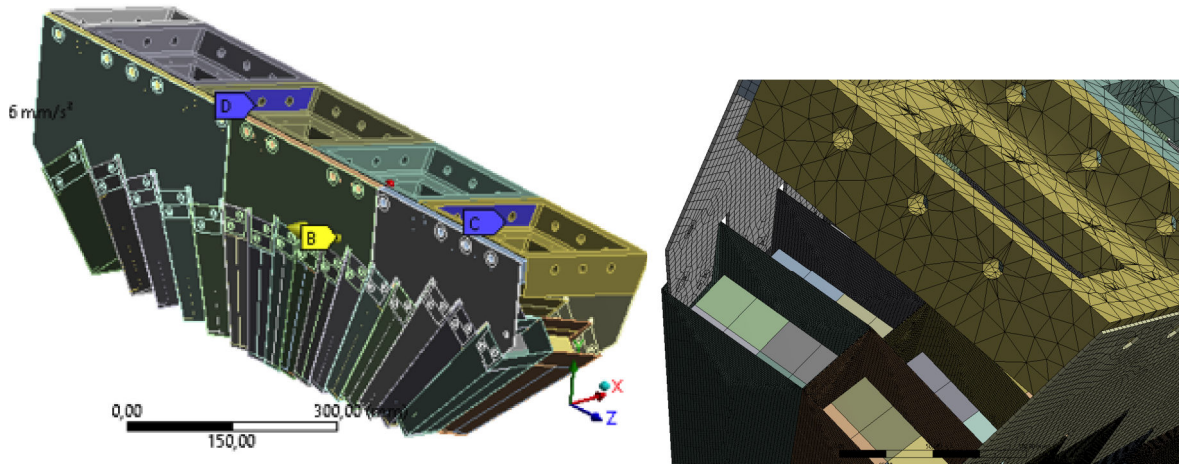

Fig. 4 - Drawing of the CAD model (left) used to define the 'segment' assembly. Two lines of 16 CFRP parts each, in contact side-to-side and front-to-back, supported by 5 tiles and tabs. The tiles were fixed as if placed by an external structure using some fixture at the dark locations. The gravity was applied as if the segment was in horizontal position. The mesh defined in the model (right): tiles: 15 mm tetrahedral elements; tabs: 5 mm hexahedral elements; CF-parts: 2 mm hexahedral elements.

We remark, additionally, that the actual whole assembly, corresponding to 8 segments together, and otherwise to 16 rings together, will add extra rigidity to the structure. Thus even if the results presented now for the partial models were underestimated, the rigidity of the whole structure would correct the deflection values into smaller values.

To have a better picture of the reach of our results, we must consider also the uncertainty and quality of the production of the parts and bundles made of CFRP (Casarejos, 2014). The inner volume of the parts was obtained within a 0.05 mm tolerance in any plane. However the outer surfaces and edges are not so tightly constrained. Additionally the parts were glued together, in a full handcraft process. The measured fluctuations in envelope dimensions reach up to 2 mm. The deformation values expected according the models, even if corrected in a 300% factor, remain well below the production and assembly tolerances.

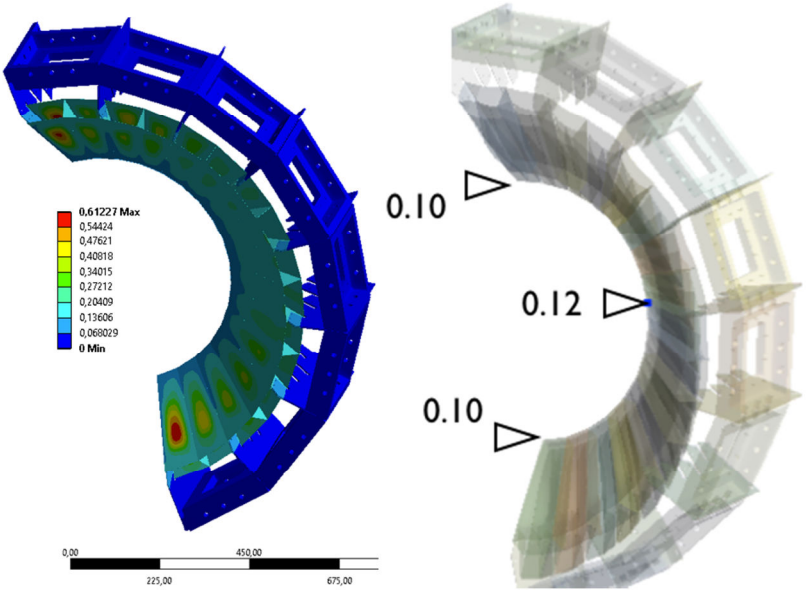

Fig. 5 - The FE model produced the total deformation of the ring structure under gravity. The contour plot (left) shows that the innermost edges reached values below 0.2 mm and the deflections at the flexible faces of the parts. The reference points where taken at the maximum deflection locations (right).

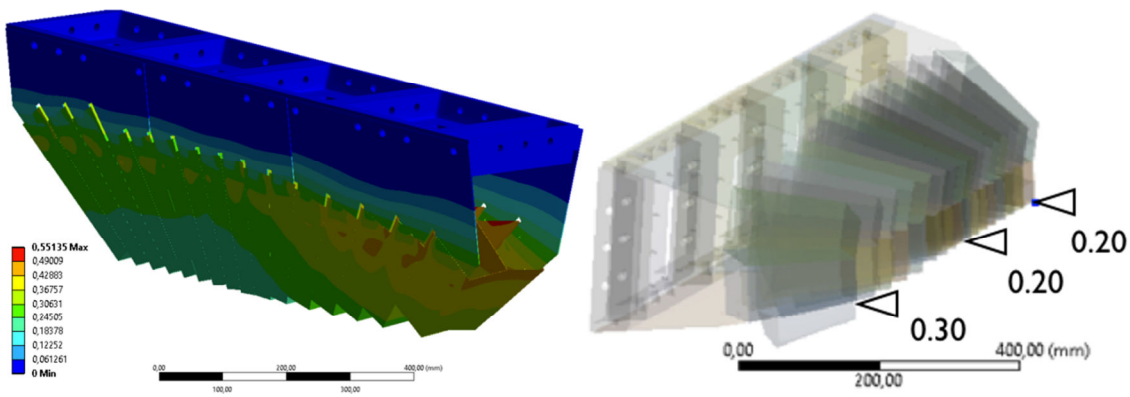

Fig. 6 - The FE model produced the total deformation of the segment structure under gravity. The contour plot (left) shows that the innermost edges reached values below 0.3 mm and the deflections at the flexible faces of the parts. The reference points where taken at the maximum deflection locations (right).

CONCLUSIONS

In our study we wanted to produce a FE model robust and reliable enough, as to be used as reference for the design phase of a laboratory detector. The needs demanded a light and rigid structure. The design was based in a honeycomb like structure, built with thin-wall parts, and made of CFRP material. The complexity of the FE model arising from the many parts, features and details, was a tough bottleneck for having such design tool.

We studied a collection of models with assumptions for linearization of material and contacts, able to produce reliable results. For the validation, we mounted a test bench of limited size, but including all the key details. We successfully defined a model able to reproduce the results, with sound assumptions. This model was then applied to much bigger assemblies, with a limited time input for both the model definition and the calculation resources involved.

We studied as reference examples two case structures that gave important information about the deformation expected in the assemblies. We found a remarkable rigidity in the CFRP structures, which implies very limited deformations in reference points. Moreover, the values obtained are well below those values of production tolerance and assembly.

These partial results are very important to assess the expected calculation needs for the behaviour of the whole structure. We have defined a tool that can provide with reliable results for the design phase of the device including the external structure.

ACKNOWLEDGMENTS

This work was partially supported by the Ministerio de Economía y Competitividad (Spain), reference FPA2015-69640-C2-2-P, and by Xunta de Galicia (Spain) under the program Grupos de Referencia Competitiva', reference GRC2015/016. López-Campos gratefully acknowledges the funding by Universidade de Vigo (Spain) under the program 'Axudas predoutorais', reference 00VI 131H 641.02

REFERENCES

[1]-The Technical Design Report of the CALIFA detector (2014) can be found at http: //www.fair-center.eu/for-users/experiments/nustar/nustar-documents/technical-design-reports.

html

[2]-Casarejos E., et al., The mechanical design of the BARREL section of the detector CALIFA for R3B-FAIR, EPJ Web of Conferences, 11037 (2014)

[3]-Casarejos E., et al., Design and construction of the structure of the DEMONSTRATOR of the CALIFA detector for R3B-FAIR using carbon-fiber composites, EPJ Web of Conferences, 11038 (2014)

[4]-Chretien N. Numerical constitutive models of woven and braided textile structural composites. Master Thesis, Faculty of Virginia Polytechnic Instit. and State University (2002)

[5]-Ito Y., Toyoda J., Nagata, S. Interface pressure distribution in a bolted flange assembly. ASME 77-WA/DE-11 (1977)

[6]-Naik N.K, Ganesh V.K. An analytical method for plain weave fabric composites.6 - Composites 26 (1995) 281-289

[7]-Shigley J. E., Mischke C. R. Mechanical Engineering Design (5th ed.). McGraw-Hill, New York, USA (1989).