QUALIFICATION TESTS OF EUROSTAR 3000 XL CENTRAL TUBE

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OVERVIEW

EADS CASA Espacio have developed an innovative structural concept for the Eurostar 3000 XL Central Tube, which consists in a CFRP monolithic shell single piece composed of a cylindrical and a conical part.

The tube is manufactured using Fibre Placement technology and presents important benefits with respect to the previous concept in terms of mass and cost savings.

The qualification of the structural model has been performed in CEPA (Test Centre for Aerospace Programmes), which is a test Centre managed jointly between EADS CASA Espacio and INTA.

This paper presents the logic and details of the whole Structural Test Campaign including Stiffness, Global and Local Strength cases and gives an overview of the main results obtained during the tests.

1. INTRODUCTION

EADS CASA Espacio is involved in the use of new manufacturing technologies in order to define new structural concepts and to improve the existing ones.

In particular, the use of automated manufacturing technologies allows for a real optimisation of the composite lay-ups, a simulation of the manufacturing process, and a recording of the actual configuration of the manufactured lay-up.

The development of the new central tube of the Eurostar 3000 LX is a practical application of this technology. Fibre placement technique is used to manufacture in a single piece the cone-cylinder shell. Monolithic construction was selected for the shell, with a thoroidally shaped cone-cylinder transition. The lay-up configuration is tailored (piles orientation, total thickness ...) along the monolithic shell.

An additional challenge in the development of this structure was to replace an existing sandwich configuration with no impact on the rest of the satellite structure components, so the qualification of these components were not questioned.

This new central tube concept development was supported by an exhaustive development test campaign intended to validate the local details of the proposed design. The final qualification was acquired with a full-scale static test of the central tube and verification at satellite level performed by EADS Astrium.

The development of Eurostar 3000 program was based in the following main goals:

• To increase the capability of the system from 5 Ton to 6.6 Ton

• To reduce the cost of the product with a minimum development cost and without risk for the parts of the satellite qualified in the previous definitions and not modified during this development.

Taking into account these premises, the main objective was to modify the main body of the platform (Central Tube) for all configurations, using the last technologies to manufacture and assembly.

The proposed structure design has been established to meet all the structural requirements (buckling, stiffness, dynamic modes, strength...) plus all the geometrical constraints imposed by the existing platform design.

The proposed solution is based on the manufacturing of all the central tube structure making use of the Fibre Placement technology. This is an automated manufacturing technique that brings together the advantages of the two most common automated methods for composite materials manufacturing: Filament Winding (FW) and Automated Tape Laying (ATL).

The main advantages of this method are related to a higher quality due to an accurate fibre orientation, better compaction and thickness control and a better repeatability of the final product. At the time the productivity on repeated series is greatly improved as result of an automated process. The FP process includes an initial optimisation phase made after the simulation of the complete manufacturing sequence. This allows for reductions of scrap material, detection of errors and optimum tailoring of the manufacturing jigs.

2. QUALIFICATION LOGIC

The different E3000 configurations were qualified using one of the possible configurations as reference. The other configurations were qualified by similarity and analysis.

The configuration was qualified with the following static tests:

a) Stiffness Test.

The main objective was to verify the stiffness matrix of the central tube and to correlate the FEM. Three cases were tested:

- Compression Load
- Moment Load
- Combined (Compression + Moment + Shear) Load

b) Strength test

To verify under the critical load cases the behaviour of the structure.

c) Local load cases

To verify the local behaviour, in a real structure of the critical areas like SM Floor, T-cleats and Solar Array attachment.

The qualification of the structure was stated not only with this static tests, but using the results of the development tests as a base for the analysis of the local areas of this structure and in order to guaranty the transmission of loads to the rest of the platform in order to maintain the qualification of the rest of the satellite (see figure 1)

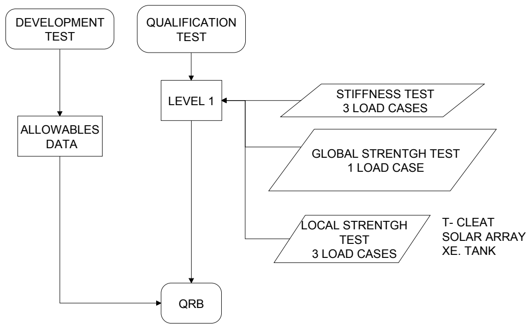

Fig. 1. Qualification logic

3. CEPA TEST CENTRE

The qualification tests were performed in CEPA (Test Centre for Aerospace Programmes), which is a test Centre managed jointly between EADS CASA Espacio and INTA.

This Test Centre was preliminary designed to provide response to the needs of the qualification of big the structures belonging to the launcher Ariane 5 and evolved to include all the means to qualify the Primary Structures of satellites. Example of qualified satellite structures are the corresponding to XMM and Herchel Plank.

The test centre is equipped with the required elements to perform the complete static qualification campaign of large structure. The hydraulic load control and the data acquisition systems are the principal elements of the laboratory, completed by a large test area which includes two test slabs at two different ground levels. The facility also includes a data monitorisation and post-processing, and provides remote access to the test data ('tele-testing') as a standard feature. A designated team of experienced personnel is in charge of insuring the execution of the test campaigns in accordance with the requested time schedules.

The static test centre is housed on a large aircraft hangar (see Fig.2), located within INTA facilities. The test centre occupies an area of 40×40 m^2 and is divided into three main areas:

- Control room and customer room
- Area for the test set-ups
- Areas for storage of test equipment and preparation of test set-ups

The area for the erection of the test set-up divided into two zones: an area of 15×30 m^2 where two reinforced concrete slabs with attachment rails are available and an adjacent area of 25×30 m^2 reserved for the installation of self-supported test set-ups. Sufficient space is also reserved for the temporary storage of the test tooling for on-going tests and for shipment of the test specimens.

The main reinforced concrete slab is located at ground level and covers an area of 10×18 m^2 . It is provided with 17 rails separated 1m with a load carrying capacity of 200kN/m for distributed loads and 80kN for concentrated loads (See fig. 2).

A second test slab of 10×10 m^2 with 9 rails and with the same load carrying characteristics is located in a pit at 6.2m below the ground level, specifically designed for test set-ups where the total height may be a restriction for other test facilities.

Adjacent to the test slabs there is an area which is designed to house those test set-ups not requiring a floor to react the loads. Two areas of 10×10m^2 are reserved for that purpose. The remaining area is used for temporary storage of test jigs in process of completing a set-up, for instrumentation of structures and for the reception and dispatching of the test specimens.

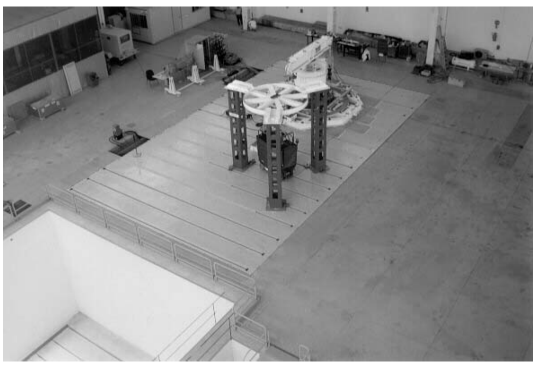

Fig. 2. Aerial view of the main slab

The area is provided with a crane with a load capacity of 8 Ton, covering an area of 37×35 m^2 and giving a height under the hook of 12.5m in all the test area and of 18.7m on the test slab located in the pit.

The Load Control System is based on a MTS Aero-90 LT closed loop digital control system operated from a host PC running on Windows NT with the following main characteristics:

22 closed loop control channels with continuous data acquisition

1 hydraulic pressure unit MTS 505.11, max working pressure of 207 bar, max flow of 42 l/min

1 hydraulic service manifold MTS 293.12 A-02

3 hydraulic service 8-channels manifolds

22 servo-valves with load abort system

The system is complemented with the corresponding software which gives an interface to the user for the configuration of a test sequence, the selection of the loop control parameters, the definition of the alarm and abort criteria and to display the load data during the test execution.

A number of hydraulic loading cylinders are part of the standard equipment of the test centre. All are equipped with the corresponding load measurement sensor of adequate range. The number of units and types were selected after the requirements of the initial set of structures to be tested. Nevertheless the list is being updated continuously as new tests are being configured. Data Acquisition System

The architecture of the Acquisition System comprises means to control and monitor up to 2000 channels for a single test including real time continuos data acquisition mode on a number of critical channels for test monitorisation

The laboratory has a stock of 270 displacement sensors with measurement ranges from 3 to 50 mm as standard equipment. In case of a specific need the test centre has the capability to provide any type of sensor for the measurement of the required physical magnitude (displacement, temperature, pressure, acceleration…).

4. TESTS DESCRIPTION

Both stiffness and strength test were performed in the same test configuration (see figure 3).

The test article were fixed to the floor by means of test rig which simulates the launcher payload adapter through a clampband to simulate the real fligh conditions. The whole set up is fixed to the floor through the rails of the main test slab.

It has to be mentioned that the clamp band used in the test is the qualification model of the LPSS 1194 that EADS CASA Espacio is developing and therefore has all the properties of a standard flight clamp band although with a Safety Margin higher than 2 as required for a test tool.

A loading cylinder was attached to the upper interface of the central tube to permit to introduce global axial and shear loads and bending moments.

Fig. 3 General view of the test set up

The structure was instrumented with around 135 strain gages of triaxial and biaxial type with a total of 390 measurement chanels.

A set of 36 displacement transducers and 12 inclinometers were used to measure the displacements and rotations of the required locations in order to verify the stiffness at the different interfaces. The transducers were set on an external auxiliary test rig decoupled from the test specimen.

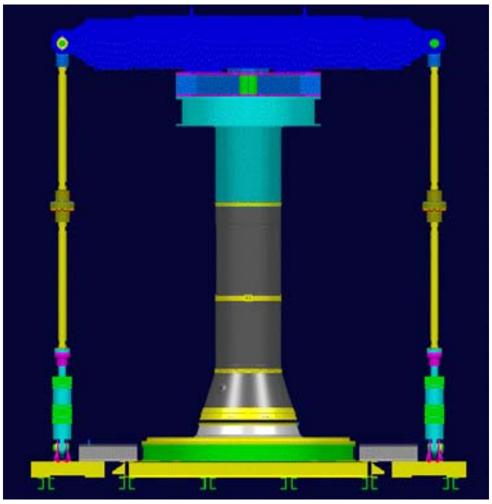

Fig. 4. Stiffness test set up for axial and pure bending moment loads

The static stiffness of the tube was verified by loading the upper interface with three different set of loads, corresponding to Compression Load, Moment Load and Combined (Compression + Moment + Shear) Load cases as schematically shown in figures 4 and 5.

The strength global cases include additional loads at other levels to simulate the the required qualification load level at any interface (see figure 6)

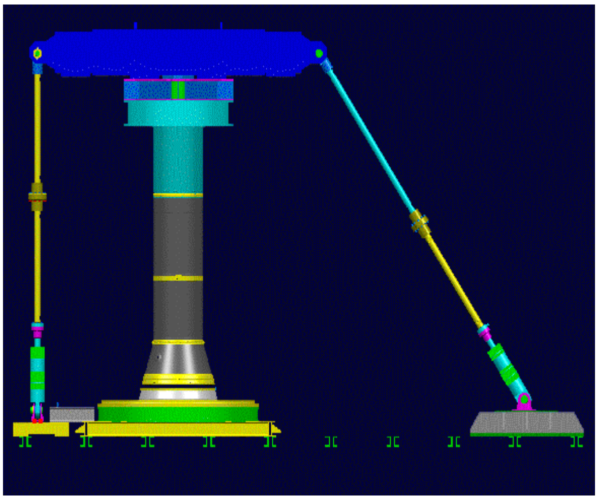

Fig. 5. Stiffness test set up for combined axial, shear and bending moment loads

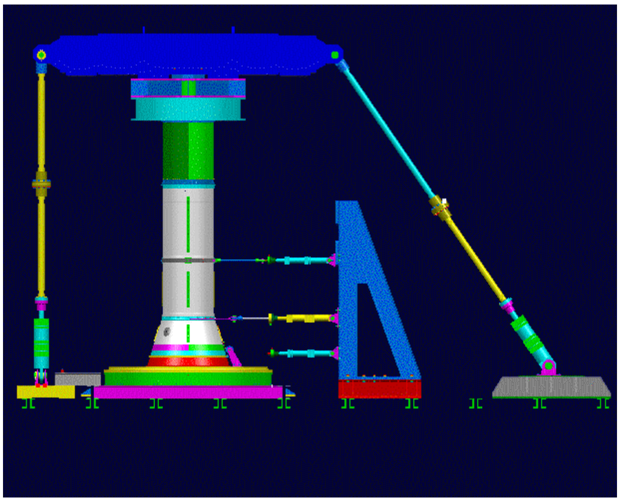

Fig. 6. Test set up for Global strength load cases

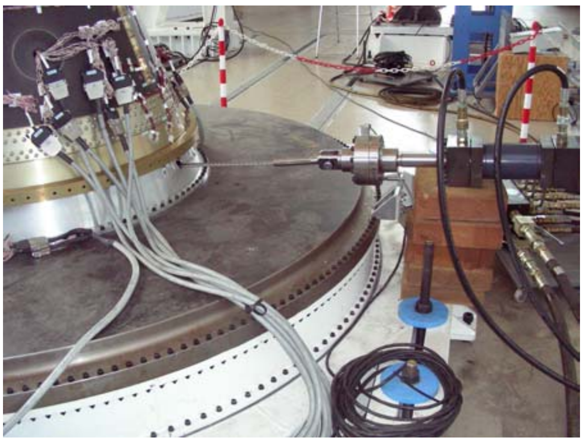

Fig. 7. Detail of the local test of the inner tank

The Xenon tank is simulated by a tank dummy located inside the cylinder attached to it through the actual tank inserts and the load was introduced by means of a set of cables and pulleys (see fig. 7).

SM Floor, T-cleats and Solar Array attachment local loads were also introduced by local jacks, cables and pulleys. A detail of T-cleat local test is shown in figure 8.

Fig. 8. Detail of the local test of the T-cleat test

5. SUMMARY OF THE TEST RESULTS

5.1. Stiffness tests

Stiffness test results have shown in general a good linearity of the measurements except in the vicinity of the clamp band but in any case they have permitted the derivation of the stiffness matrices and a useful exploitation of the test results.

In general the first comparison between predicted and test results values showed a significant level of discrepancy. Main reasons for this discrepancy are the lack of modelling of the lower test rig and the underestimation of the stiffness of the clamp band. Also the properties of the CFPR materials were corrected since the analysis assumed theoretical properties. Measured properties from material acceptance tests and differences between tension and compression Young's Modulus helped in correlating experimental and predicted results. Once correlated the FEM the data from analysis and tests are fully comparable.

Figure 9 shows the comparison between predicted and test results in the upper section of the tube, measured at the interface with the load cylinder. Differences less than 5 per cent are observed. The same good correlation is obtained at the other sections of the tube.

Figures 10 and 11 show respectively the axial and radial displacements for the bending moment case. In this case the difference between predicted and measured value can be up to 14 per cent for some points, although the different in the global stiffness taken into account the displacements of all the points of the section is less than a 10 per cent.

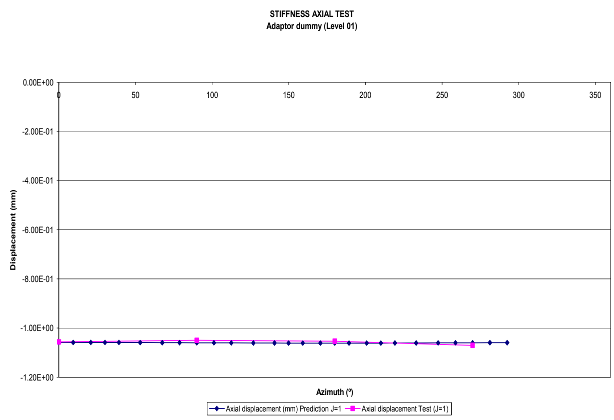

Fig. 9. Axial displacements for the axial load case test at the upper section.

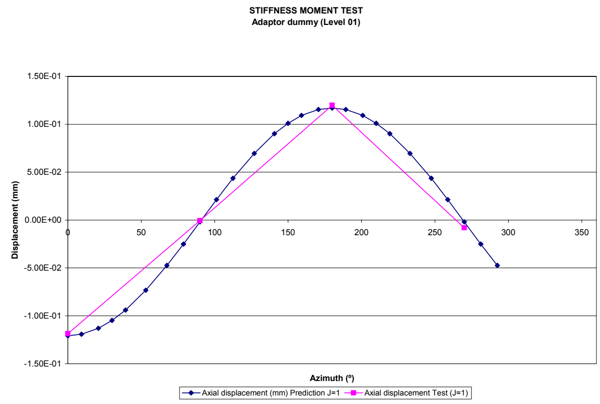

Fig. 10. Axial displacements for the moment load case test at the upper section.

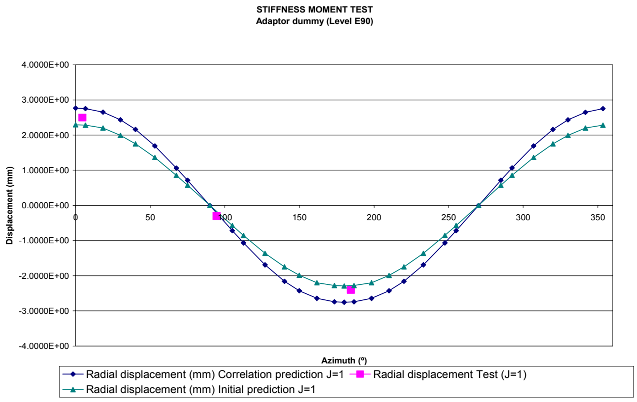

Fig. 11. Radial displacements for the moment load case test at the upper section.

5.2. Strength tests

The strength tests have confirmed the capability of the structure to withstand the qualification loads without damage. Good linearity and zero return of the main strain gages demonstrated that no yielding were produced during the test. As in the stiffness test, the main deviations from linear behaviour are observed in the sections around the clamp band.

The predicted strains in the most critical locations have a significantly good level of correlation with the test results. Figures 12 to 14 show the strain in different locations of the central tube comparing the test results with the predictions before and after the correlation exercise explained before.

It has to be remarked that the correlation exercise performed includes uncertainty analysis to estimate the impact of the errors in the FEM model and in the test set up. The basis for such analysis is described after in 5.3.

After the complete evaluation of test data it can be stated that the positive safety margins presented in the Design Phase have been confirmed

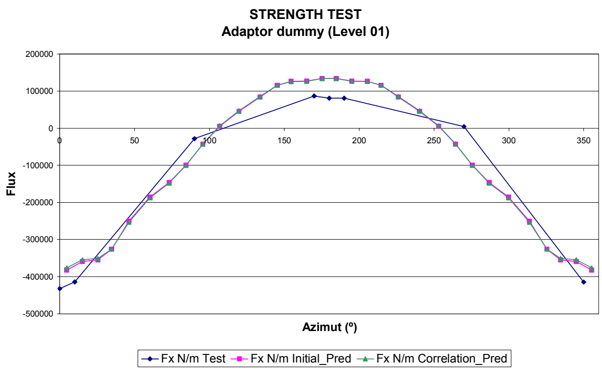

Fig. 12. Strain in the upper interface of the Central Tube

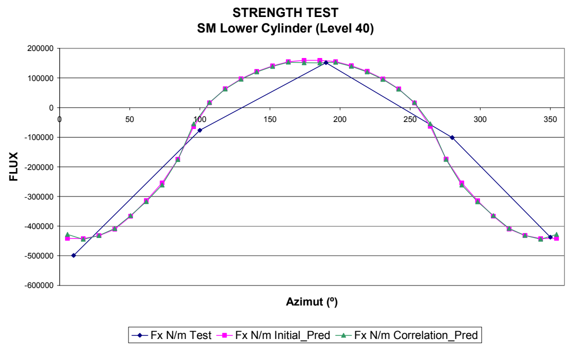

Fig. 13. Strain in the SM lower cylinder

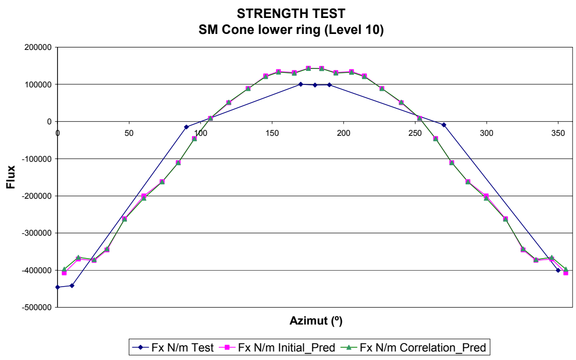

Fig. 14. Strain in the SM cone lower ring

5.3. Uncertainty analysis

In order to achieve a more accurate analysis of the prediction deviations with respect to the test measurements uncertainties arising from the predictions and from the test measurements are evaluated and considered in the correlation analysis.

Uncertainties involved in the predictions can be due to:

FEM mesh, so the mesh sizes, type of elements… are a source of errors and uncertainties. The mean size of plate elements in the Eurostar 3000 central tube FEM is 75mm x 30mm. For this model a ± 5% uncertainty can be established.

Elastic modulus of the material (VICOTEX M18/32%/M55J/145). From EADS-CASA data base in which UD laminate test values of this CFRP material are contained, the following statistical data are applied:

UD Modulus	CV%
Longitudinal tension	5.65%
Longitudinal compression	7.60%
Transverse tension	1.87%
Transverse compression	1.84%
In plane shear	2.76%

CFRP shell thickness. Data of the test model have been achieved by dimensional verification in a DEA machine after the shell manufacturing.

All the uncertainties identified in the previous paragraphs affect the prediction as the various data involved are used as inputs of the FEM.

The uncertainty in the FEM response magnitudes (displacements, rotations and strains) due to the contribution of each deviation identified above (shell radius, shell thickness, elastic modulii) is calculated from the results obtained from the FEM after implementing the respective deviation (see detailed formulation below)

For each uncertainty the procedure presented in the scheme below (see table 1) is applied.

Finally the individual uncertainty components are combined using the Root-Sum-of-Squares method (RSS)

$$(STD)_{total} = \sqrt{\sum_{1}^{n} STD_i^2}$$

The same exercise is performed for the test results assuming errors coming from elements of the test set up and instrumentation. In particular the following errors have been considered:

Displacement transducer (APEK-MB-5): 0.15%

Inclinometers (SEIKA NB2): 4.00% S

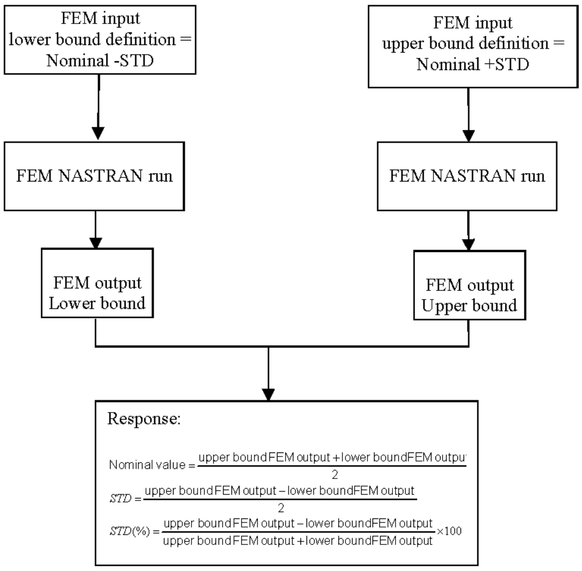

Table 1. Logic for the uncertainty analysis

Strain

Uncertainty due to the gauge factor. The gauge factor (**GF**) participates in the relationship between strains (ε) and relative change in the gauge electrical resistance relative variation in the Wheatstone bridge, according to the following equation:

$$\varepsilon = \frac{1}{GF} * \frac{\Delta R}{R}$$

R= 350 Ω

ΔR/R= 0.3 % uncertainty

GF: Triaxial gauges **1.98 ± 1%**

biaxial gauges: **2.01± 1%**

The uncertainty in the strain measurements is derived from the above uncertainties, as follows:

$$\frac{\Delta\varepsilon}{\varepsilon} = \sqrt{\left(\frac{\Delta GF}{GF}\right)^2 + \left(\frac{\Delta R}{R}\right)^2} = 1.044\%$$

Uncertainty due to the transverse sensitivity. The transverse sensitivity uncertainty is zero for the biaxial gauges according to the supplier data. In the case of the triaxial gauges, the uncertainty of this sensitivity is about 0.2%, -0.1% depending on the gitter. The uncertainty in the strain measurement, obtained by applying the uncertainty propagation formulation, becomes negligible.

Uncertainty due to gauge installation misalignment. The misalignment maximum error is estimated in 1°.

The uncertainty in the strain measurements with respect to the strain gauge position is estimated as follows:

$$STD(\varepsilon_x) = \frac{\gamma_{xy}}{\varepsilon_x} * \delta\theta$$

$$STD(\varepsilon_y) = -\frac{\gamma_{xy}}{\varepsilon_y} * \delta\theta$$

$$STD(\gamma_{xy}) = \frac{(-2\varepsilon_x + 2\varepsilon_y)}{\gamma_{xy}} * \delta\theta$$

$$STD(\varepsilon_2) = \frac{(\varepsilon_1 - \varepsilon_3)}{\varepsilon_2} * \delta\theta$$

Finally the individual uncertainty components are combined using the Root-Sum-of-Squares method (RSS) in a similar way as explained for the prediction uncertainties.

$$(STD)_{total} = \sqrt{\sum_{1}^{n} STD_i^2}$$

Once updated the FEM model more reasonable results, inside the accepted range of differences between predicted and test results were obtained.

6. CONCLUSIONS

A new concept for the Central Tube of Eurostar 3000 has been developed with a significant improvement of performances.

A static test campaign has been performed to verify the capability of the structure to withstand the specified loads.

A very detailed uncertainty analysis has been performed to correlate the analytically predicted and the experimental test results.

The qualification test campaign demonstrated the fulfilment of all the requirements of stiffness, strength and stability in accordance with the specified data.