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C-27J FEM Version 3.0 Enhancement and Verification

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ABSTRACT

The Royal Australian Air Force (RAAF) has commenced a fleet acquisition of C-27J aircraft (AIR8000 Phase 2) to support RAAF tactical airlift capability requirements. As part of the Structural Substantiation Program, a global Finite Element Model (FEM) of the C-27J airframe was obtained from the Original Equipment Manufacturer, Alenia Aeronautica. A global airframe FEM is an important supplementary tool to aid in support of both current and future RAAF C-27J structural integrity management. In 2013, Defence Science and Technology Group completed a preliminary review of the C-27J global FEM and recommended several areas of model enhancement, including specific C-27J FEM verification and validation activities. The key enhancements are: inversion about the global x-axis for all model and load files, incorporation of beam element section properties representative of design section geometry, and finally, creation of a uniform set of engineering units to be used consistently for the model geometry, model materials, and applied loads. Model verification was carried out following application of each of these enhancements and reported. Pending experimental validation, the enhanced and verified C-27J global FEM, known as "C-27J_GFEM_DSTG-v3.0", is a linear elastic internal loads model that will be useful in providing global loads results such as wing tip displacements, field stresses, running loads, and connection forces.

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Executive Summary

The Royal Australian Air Force (RAAF) has commenced a fleet acquisition of C-27J aircraft (AIR8000 Phase 2) to support RAAF tactical airlift capability requirements. As part of the Structural Substantiation Program, a global Finite Element Model (FEM) of the C-27J airframe was obtained from the Original Equipment Manufacturer (OEM) Alenia Aeronautica. A global airframe FEM is an important supplementary tool in support of both current and future RAAF C-27J structural integrity management. In 2013, Defence Science and Technology (DST) Group completed a preliminary review of the C-27J global FEM and recommended several areas of model enhancement, including specific C-27J FEM verification and validation activities. The objectives of these enhancements were: alignment with DST Group model orientation norms, improved useability, alignment with design baseline data, and a reduction in the potential for usage errors.

Presented in this report, the key enhancements are: inversion about the global x-axis for all model and load files, incorporation of beam element section properties representative of design section geometry, renumbering and formatting of data files and finally, restoring the model to a uniform set of engineering units to be used consistently for the model geometry, model materials, and applied loads. The model is now structured in a manner that allows independent operation on any number of the sub-models constituent to the global FEM. Furthermore, substructures are numbered in an orderly fashion that allows new FEM entities to be introduced consistent with the numbering regimes applied, and thus easily spliced into the global FEM. Model verification was carried out following the application of the enhancements and is reported herein. However, assessment has also identified some remaining limitations relating to the applicability of the original applied loads as received from the OEM.

Pending experimental validation, the enhanced and verified C-27J global FEM, known as “C-27J_GFEM_DSTG-v3.0”, is a linear elastic internal loads model that will be useful in providing global loads results such as wing tip displacements, field stresses, running loads, and connection forces. The limitations associated with this model demand focussed consideration by all users.

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Abbreviations

ADF	Australian Defence Force
ASIP	Aircraft Structural Integrity Program
bdf	Bulk data file
DST Group	Defence Science and Technology Group (formally the Defence Science and Technology Organisation [DSTO])
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FEM	Finite Element Model
MPC	Multi Point Constraint
OEM	Original Equipment Manufacturer
RAAF	Royal Australian Air Force
RBE	Rigid Body Element
SI	System International
SSP	Structural Substantiation Programme

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1. Introduction

The Royal Australian Air Force (RAAF) has commenced a fleet acquisition of C-27J aircraft (AIR8000 Phase 2) to support RAAF tactical airlift capability requirements. The C-27J is manufactured by Alenia Aermacchi (Alenia) of Italy. A Nastran C-27J global Finite Element Model (FEM), created by Alenia and used during the EASA and FAA C-27J Type Certification process, has been identified as a valuable tool to supplement RAAF in-service support of the aircraft. Therefore, the Defence Science and Technology (DST) Group sought and received from Alenia, via [1], a copy of the C-27J Nastran global FEM and some of its accompanying static and fatigue external loads files. Under DST task 07/384, formal acceptance of the Alenia C-27J FEM by the RAAF requires independent verification and validation (IV&V). The aim is to have a high quality and user friendly model suitable for the verification and validation activities, Structural Substantiation Program (SSP) support, and Aircraft Structural Integrity Program (ASIP) investigations.

In 2013, DST Group completed a preliminary review of the C-27J FEM and recommended several areas of model improvement, including specific C-27J FEM verification and validation activities [2]. DST Group was subsequently requested via [3] to complete verification activities for the C-27J FEM. In order to make the FEM more user-friendly and for it to pass the final verification checks, a variety of changes to the model were required.

This report addresses the incorporation of several key recommendations detailed in [4]. The enhancements documented here are based on a starting point of global FEM v2.0. These include the incorporation of beam section properties that more accurately reflect the design, spatial inversion of the model about the global x-axis to orient the model consistent with DST Group norms, complimentary inversion of the model loads files, applying consistent SI engineering units throughout, and verification checking of these changes. Finally, the current state of the C-27J global FEM and recommendations for further work are discussed.

2. Overview of Original Alenia Global FEM

The Alenia C-27J Nastran finite element internal loads model was received by DST Group from Alenia in 2012 as per [1]. The as-received data included four Nastran control files, the associated bulk data files (*.bdf) and accompanying pressure, static, and fatigue loads files. In the original DST Group review of the as-received Alenia C-27J Nastran FEM [2], the bulk data files listed in the control file *run_static_fusol_JCA_ult.dat* were examined. The subsequent initial enhancement and verification work at [5] and the work documented in [4] scrutinised and enhanced the associated bulk data files.

2.1 Description of the Alenia Model

The global FEM as provided by Alenia included eleven submodels comprising beam and shell elements. The global model is shown in Figure 1. The eleven submodels and their respective bulk data files, re-named in English, are listed in Table 1. Similarly, load and pressure files are listed in Table 2. The connections between submodels are described in Table 3.

The original DST Group review of the C-27J global model in [2] found the Alenia FEM did not successfully[1] complete a Nastran run. In the received control deck for the Nastran analysis, the parameter BAILOUT was set to the value -1, which causes the programme to continue processing with near singularities, which would otherwise cause the programme to halt. The Nastran results showed excessive aft fuselage frame distortion. It was concluded that without further investigation and corrective action, the global FEM did not appear to be suitable for the intended ASIP activities. Versions 1.0 and 2.0 of the C-27J Global FEM as per [4] and [5] addressed many of the technical issues. These are summarised in Figure 2. This brought the model to a functionally workable state however it was inconsistent with DST Group sign convention norms, contained misleading engineering units and was questionable in terms of its faithfulness to the aircraft design geometry baseline. This report addresses those items required to bring the model to v3.0 (also as per Figure 2) from v2.0 and the associated checking activities conducted to verify the v3.0 model.

3. Description of Current Enhancement and Verification Procedures

The aim of the current enhancement and verification activity is to leverage from the previous DST Group verified FEM v2.0 to produce a useful, workable, high quality tool for subsequent verification and validation activities, SSP support and likely ASIP investigations. On the basis of completed work as per [6], [7] and the development work for FEM v2.0, it is assumed that the issue of producing a design representative model is partially addressed. Thus, detailed checking of geometry is confined to checking of beam section property incorporation (as per Section 3.3 of this document). The enhancement and verification process from v2.0 to v3.0 was completed in five stages: inversion of the model about the global x-axis, inversion of loads about the global x-axis, incorporation of beam section properties (via Nastran PBMSECT function), incorporation of engineering unit corrections and finally, verification of the global model.

[1] Here a Nastran run is considered "successful" when BAILOUT is off, AUTOSPC=NO, K6ROT=100 and no Nastran FATAL errors are generated.

3.1 Inversion of Model about Global X-Axis

In order to maintain the syntax of the individual Nastran files, the global x-axis rotation was facilitated through the use of Visual Basic code that manipulated the individual bulk data files directly. Every grid point was inverted about the global x-axis, by multiplying the global z and global y values by minus one.

To account for model aspects defined by local coordinate systems, each local coordinate system was also inverted. This was executed through operations on the spatial points that define these coordinate systems (CORD2R approach, as per [8]). Figure 3 presents the derivation of the mathematical operations used. This operation was performed directly upon the Nastran bulk data files through the use of Visual Basic code and verified through visual inspection of the inverted model in Patran.

To complete the model inversion process, based on the elements used, beam and bar elements required their orientation and offset vectors to be inverted. This was performed by Visual Basic code that manipulated the individual bulk data files directly. Consistent with previous vector inversions, orientation vectors of the general form (X1,X2,X3) were replaced with (X1,-X2,-X3). Similarly, offset vectors of the general form (N1,N2,N3) were replaced with (N1,-N2,-N3). The inverted outputs maintained their original level of precision.

All of the mathematical operations described in this section are captured in the Visual Basic macro "Z-axis transform FEM" as per [9].

3.2 Inversion of Loads about Global X-Axis

To maintain correct loading of the FEM, the loads applied required adjustment to account for model inversion. As such, the loads that act upon the global FEM were also inverted in space (rotated about the global x-axis by 180 degrees). This was executed through actions applied directly to the Nastran bulk data files using Visual Basic code. For forces where the general notation for the force vector is (N1,N2,N3), the inverted vectors (i.e. rotated about the x-axis by 180 degrees) take the form (N1,-N2,-N3). This same approach applies for moments, i.e. the N2 and N3 terms have their signs reversed. Pressures, due to the nature of being applied normal to surfaces, required no change in this sense. All of the mathematical operations described in this section are captured in the Visual Basic macro "Z-axis transform FEM" as per [9].

3.3 Incorporation of Beam Section Properties

In [10] DST Group identified a need for replacing a set of bar elements (Nastran type CBAR) with more accurate beam section property data that accurately reflected the C-27J certification basis. In [7], QinetiQ Australia provided DST Group with beam section files that captured design representative cross-section geometry. The deliverable included Nastran cards (PBMSECT), which provided accurate cross-section data for the beams nominated by DST Group for this exercise. Some of the benefits offered through this approach include visualisation of beam sections within Patran and by corollary, the ability to ensure that element placement geometry, offsets, and orientations are correct. The original bar element information gives the spatial position of the bars and their points of connection.

The first step in the process of incorporating the revised beam sections was to change the associated CBAR elements. This is due to the fact that the Nastran CBAR element was found to be incompatible with the PBMSECT definition. In order to overcome this, the bar elements were changed to the Nastran beam element type (CBEAM).

The second step in the process was to remove the related bar element property cards (PBAR entries). The PBAR entries were tied to the legacy CBAR elements, with the PBAR data being the element material and section properties (i.e. 2nd moments of area, torsional constants, shear constants, etc.). The associated PBAR entries were simply removed by prefacing these entries with the Nastran comment identifier '$'. In this way, the historical data remains available if required at any stage in the future.

The third step in the process was pointing the new beam elements to their property cards (which took the form of PBMSECT entries). This was simply a case of mapping the CBEAM property identification number to the PBMSECT property identification number. Refer [7] for the listing of beam section property files.

The final step, to complete the beam property incorporation, was correction to the beam offsets and orientations. This was achieved by successive steps of examining the model in Patran, determining the required vector corrections (by inspection of misalignments to adjacent parts), recording the required correction vectors and finally incorporating these correction vectors into the Nastran bulk data files.

All of the above steps were executed via Visual Basic macros, working directly with the Nastran bulk data files, as per [11], [12], [13] and [14].

3.4 Application of Consistent Engineering Units for Loads

Late in the process of developing the C-27J v3.0 model, it was discovered that the legacy model had employed two systems of units for pressure and force. Part of the model applied daN/mm^2 while elsewhere, kgf/mm^2 was used. Similarly, numerous force entries used the kgf unit system while daN is used elsewhere. It is considered both poor practice and extremely risky to apply multiple systems of units within a single model and as such, steps were taken to restore the model to consistently apply units of N and N/mm^2 throughout.

The Visual Basic macro PressureFix_v1.0 as per [15] was written to address this issue for this particular model. This macro corrects the pressure values for Nastran entries of type 'PLOAD' and 'PLOAD2', by applying the conversion factor that was previously embodied in the LOAD cards. Similarly, Nastran 'FORCE' entries are corrected. Lastly, the macro redefines the LOAD scaling factors, by dividing by the aforementioned conversion factor. In this way, the original calculations remain unchanged; only the system of units changes. This concludes the model modifications; the resultant model (with rigid body loading elements in magenta visible) is shown in Figure 4.

3.5 Verification of Global FEM v3.0

3.5.1 Verification of Inverted Global FEM

As per Sections 3.1 and 3.2, several mathematical operations were required in order to invert the global FEM. Recognising that no loads, component geometry, material or boundary condition changes were required to produce the inverted model, checking on the completion of the inversion was identified as an opportunity, since identical results were to be expected both before and after the change. FEM checking was therefore performed at this stage (i.e. before beam section properties were modified).

The inverted model was checked by a back-to-back comparison of grid-point forces (grid point force balance), resultant force balance (Nastran type 'OLOAD'), and deformation fringe plots, for a sub-set of Ultimate load cases as per [1]. Figure 5 through Figure 8 show the global deflection response comparisons for the FE model. Table 5 shows the OLOAD comparison between the respective FE models. Figure 9 shows comparisons of the grid point force balance (total vector magnitude as a fringe, against the deformed geometry) for the respective models. As is evident from the above, near exact alignment exists for the OLOAD outputs, the deformation fringe plots, and the grid point force balance. Therefore it is concluded that model inversion has been completed successfully and without error.

3.5.2 Verification of C-27J Global FEM v3.0

As per Section 3.5.1 of this report, verification has been carried out to confirm the correctness of the steps required to invert the model and the associated loads files. The follow-on set of verification steps centres on verifying the correct incorporation of PBMSECT beam sections. Verifying the beam section incorporation involves the steps outlined below:

The first step is visually inspecting (and adjusting as necessary) the beam section offsets and orientations. This activity was performed using Patran. Several adjustments were required to the beam orientations and offsets. These are captured in [11], [12], and [13]. The corrected beam positions were confirmed by inspecting the model in Patran and are also evident in Figure 10 through Figure 19.

The second step requires the application of the macro within [15] and thus with corrections to pressures and forces applied, OLOAD outputs are compared before, and after the adoption of these changes. As is evident from Table 6, the discrepancy between the respective outputs is extremely small and consistent with computational error expectations.

The third step is performed by global deflection comparisons of the FE model. Comparison results before and after beam section incorporation are evidenced in Figure 20 to Figure 25. Differences in the global deflection behaviour are small and consistent with expectations.

The fourth step uses the DST Group developed Nastran model checking tool. This tool has been applied in the previous DSTO FEM check on C-130J [16]. This process comprises a static run with unit acceleration loading, which acts on and thus loads all nodes in the model, coupled with a normal-modes dynamic run of the model in a constraint-free state to reveal the existence of unintended grounding. Step four is the verification of the model as per this DST Group developed Microsoft Excel based Nastran FEM checking tool, the results of which can be found in Figure 26 and are explained further in Table 7. Of particular note are small changes to the aircraft centre of gravity (C of G) and mass, which are entirely consistent with the incorporation of the revised beam sections as per Section 3.3 of this document.

4. Capability and limitations of the v3.0 Global FEM

The v3.0 FEM has been demonstrated to work with the 1g load equilibrium checks as per Section 3.5.2 Step four. The enhanced and verified model is a linear elastic internal loads model that can be used to provide global loads results; for example, wing tip displacements, field stresses, running loads or connection forces. The model is coarse in nature and local geometric details are not presented. It is therefore recommended that the model is not used for local stressing without detailed local analysis of the structure, including accounting for geometric and attachment detail. Additionally, the mass of the C-27J FEM is not representative of the real structure or any payload. Therefore, results from dynamic analyses will not be realistic.

The enhanced and verified C-27J global model has been verified against the DST Group model checking criteria. The model has not yet been validated against experimental loads measurement. Validation remains necessary prior to formal use of the model (see recommendations in Section 5).

5. Recommendations for Future Work

5.1 Load Case Generation

It is recognised that the load cases provided from Alenia are intended for meeting the specific requirements of Alenia's certification activity. It is also recognised that RAAF usage characteristics are likely to differ from these cases. As such, it is recommended that due consideration is given to examining the continued relevance and applicability of Alenia's certification load cases. For example, new load cases may be considered necessary to; (a) extend or modify the certification basis of the aircraft, or (b) to provide a greater depth of detail for missions particularly relevant to ASIP activities, or (c) to allow correlation of FE derived outputs against flight test or ground calibration test activities.

5.2 FEM Outputs Study

The outputs of [6] and [7] indicate that appreciable change was undertaken to numerous beam sections within the global FEM at v3.0. Accordingly, whilst the global deflection results shown in Figure 20 through Figure 25 indicate relatively small changes, it is possible that more significant load/stress changes exist within the individual members of the airframe. It is therefore recommended that a study is undertaken to examine the changes between model versions v3.0 and v2.0, with the aim of better understanding the significance and impact of the revised internal loads carried by the structure.

5.3 FEM Validation

Future activities related to this aircraft include the planned C-27J ground calibration test and thereafter, the full-scale fatigue test. Additionally, flight tests are foreseeable. These activities will allow direct measurement of loads, stresses and deflections. This data can form an important connection between actual aircraft behaviour and the FE model predictions. It is therefore recommended that, in order to fully validate the FE model, a correlation exercise is undertaken, based on the outputs of these tests. This will establish the magnitude of test/analysis differences and from this determine the appropriate strategy for managing these differences. For example, it may be determined that test/analysis correction factors are to be employed in subsequent analyses.

5.4 Certification Basis Considerations

The analysis work performed until this point has shown several significant issues with the original Alenia global FE model. These include modelling errors that initially prevented the model from running properly (as described in Section 2.1), issues with the model configuration that caused abnormal aft fuselage frame distortion (as described in Section 2.1), issues with element type (as described in [2]) and non-trivial discrepancies with design geometry (as per [6] and [7]). The relative significance of these issues raises concerns regarding the accuracy of the original Alenia loads used for certification calculations, including certification stress dossiers for both static and fatigue analyses. It is therefore recommended that consideration is given to determining the differences between Alenia's certification loads applied within the various stress dossiers, and those that would be produced from the v3.0 global FE model. It is noted that DASA-ASI is investigating this aspect as part of compliance finding activities.

6. Conclusions

The FEM as described in this document is referred to as "C-27J_GFEM_DSTG-v3.0". The C-27J_GFEM_DSTG-v3.0 FEM is stored in a .zip file [17] as a complete Global FEM, with constituent sub-models as per the break-down detailed in Table 1. Importantly, whilst the C-27J FEM was delivered with 83 certification load cases, examination of these files does not lie within the scope of this work and as such, no load cases have been approved for use by virtue of the present activity; load cases considered appropriate for use with C-27J FEM DSGT-v3.0 are discussed in Sections 4 and 5.

Description of the enhancement and verification process for the Alenia C-27J FEM - from v2.0 to v3.0 - performed by DST Group has been presented. Enhancements to the model were made in order to address model quality issues and also to align the model to DST Group norms.

Enhancement activities included:

- model inversion to a manner consistent with the DST practice of aligning the z-axis vertically upwards (x directed aft; y directed starboard)
- inversion of loads to achieve consistency with the inverted FE model
- incorporation of beam section properties representative of design section geometry
- rectification of engineering units to a consistent SI metric basis.

Verification of the model has been performed using visual techniques, back-to-back results comparison, and the use of the DST Group Nastran FEM checking tool. The verified model "C-27J_GFEM_DSTG-v3.0" is now fit for use within the limitations discussed in Section 4. Recommendations for future work to improve the FEM have been presented in Section 5, which also serves to provide a more detailed discussion on the existing limitations.

7. References

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Tables

Table 1: Model definition files for the C-27J global FEM, as listed in the control file 'run_static_fusol_JCA_ult-dat'

Item #	Bulk Data File Name	Airframe Component
1	cargo_door.bulk	cargo door
2	stabiliser_vertical.bulk	vertical stabiliser
3	fuselage_forward.bulk	forward fuselage
4	fuselage_centre.bulk	centre fuselage
5	fuselage_aft.bulk	aft fuselage
6	wing_centre.bulk	wing – centre
7	cargo_ramp.bulk	cargo ramp
8	wing_outer_stbd.bulk	outer wing - right (starboard)_
9	wing_outer_port.bulk	outer wing - left (port)
10	stabiliser_horz_stbd.bulk	horizontal stabiliser - right (starboard)
11	stabiliser_horz_port.bulk	horizontal stabiliser - left (port)
12	stabiliser_horz_port_elevator.bulk	Horizontal stabiliser – elevator - port
13	stabiliser_horz_stbd_elevator.bulk	Horizontal stabiliser – elevator - starboard

Table 2: Nastran load and pressure files for C-27J global FEM v3.0

Item #	File Name	Load or Pressure File
1	corr_genload.LOAD	Load
2	fat_load_update_wing.LOAD	Load
3	fatigue_load_completo_magliacane.LOAD	Load
4	fus_lateral.LOAD	Load
5	fus_loop01.LOAD	Load
6	fus_loop02.LOAD	Load
	load_cards_ult.LOAD	Load
7	wing_load_loop2.LOAD	Load
8	load_cards_ult.LOAD	Load
9	c27j_cargo_door.PRS	Pressure
10	c27j_cargo_ramp.PRS	Pressure
11	c27j_fuselage_aft.PRS	Pressure
12	c27j_fuselage_centre.PRS	Pressure
13	c27j_fuselage_forward.PRS	Pressure
14	c27j_wing_centre.PRS	Pressure

Table 3: Listing of interface files for connecting C-27J submodels (v3.0 FEM)

Item #	Interface filename	Connected Submodels
1	ic_cargo_door_to_fuse_aft_hinges	Cargo door and door hinges
2	ic_fuse_aft_to_cargo_door_hooks	Cargo door and door hooks
3	ic_fuse_aft_to_cargo_ramp_hooks	Cargo ramp and ramp hooks
4	ic_fuse_cntr_to_cargo_ramp_hinges	Cargo ramp and ramp hinges
5	ic_fuse_aft_to_vstab	Vertical stabiliser and aft fuselage
6	ic_fuse_fwd_to_fuse_cntr	Forward fuselage and centre fuselage
7	ic_fuse_cntr_to_fuse_aft	Centre fuselage and aft fuselage
8	ic_fuse_cntr_to_wing_cntr	Centre fuselage and centre wing
9	ic_wing_cntr_to_wing_outer_port	Centre wing to outer wing – port
10	ic_wing_cntr_to_wing_outer_stbd	Centre wing to outer wing - starboard
11	ic_wing_cntr_to_wing_outer_stbd	Starboard outer wing to centre wing
12	ic_wing_cntr_to_wing_outer_port	Port outer wing to centre wing
13	ic_stab_horz_to_elevator_stbd	Starboard horizontal stabiliser to elevator
14	ic_fuse_aft_to_hstab_stbd	Starboard horizontal stabiliser to aft fuselage
15	ic_stab_horz_to_elevator_port	Port horizontal stabiliser to elevator
16	ic_fuse_aft_to_hstab_port	Port horizontal stabiliser to aft fuselage

Table 4: Listing of beam section property files for re-defining C-27J beam sections (v3.0 FEM)

Item #	Section property filename	Location
1	properties_pbmsect_stab_horiz_port	Horizontal stabiliser – port
2	properties_pbmsect_stab_horiz_stbd	Horizontal stabiliser – starboard
3	properties_pbmsect_wing_outer_port	Wing outer – port
4	properties_pbmsect_wing_outer_stbd	Wing outer – starboard
5	properties_pbmsect_wing_centre	Wing centre

Table 5: C-27J Global FEM – OLOAD comparison for inverted model vs. v.2.0

	File:	run_static_fusol_jca_ult_dstg							File:	run_static_fusol_jca_ult_dstg						Comparison					
	Version:	2.0							Version:	Inverted						Ti' = Ti(v2.0) / Ti(inverted)					
	OLOAD	RESULTANT							OLOAD	RESULTANT											
SUBCASE								SUBCASE													
ID	TYPE	T1	T2	T3	R1	R2	R3	ID	TYPE	T1	T2	T3	R1	R2	R3	T1'	T2'	T3'	R1'	R2'	R3'
10	FX	-4.50E+05	----	----	----	-1.19E+09	-1.11E+08	10	FX	-4.50E+05	----	----	----	1.19E+09	1.11E+08	1	1	1	1	-1	-1
	FY	----	5.04E+04	----	8.62E+07	----	7.87E+08		FY	----	-5.04E+04	----	8.62E+07	----	-7.87E+08	1	-1	1	1	1	-1
	FZ	----	----	-6.79E+03	4.80E+06	3.75E+08	----		FZ	----	----	6.79E+03	4.80E+06	-3.75E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	0.00E+00	----		MY	----	----	----	----	0.00E+00	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-4.50E+05	5.04E+04	-6.79E+03	9.10E+07	-8.10E+08	6.77E+08		TOTALS	-4.50E+05	-5.04E+04	6.79E+03	9.10E+07	8.10E+08	-6.77E+08	1	-1	-1	1	-1	-1
11	FX	-3.77E+05	----	----	----	-8.81E+08	4.51E+08	11	FX	-3.77E+05	----	----	----	8.81E+08	-4.51E+08	1	1	1	1	-1	-1
	FY	----	3.78E+04	----	3.40E+08	----	4.39E+07		FY	----	-3.78E+04	----	3.40E+08	----	-4.39E+07	1	-1	1	1	1	-1
	FZ	----	----	-5.15E+03	3.64E+08	-3.15E+08	----		FZ	----	----	5.15E+03	3.64E+08	3.15E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	-6.65E+08	----	----		MX	----	----	----	-6.65E+08	----	----	1	1	1	1	1	1
	MY	----	----	----	----	5.64E+08	----		MY	----	----	----	----	-5.64E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	1.23E+07		MZ	----	----	----	----	----	-1.23E+07	1	1	1	1	1	-1
	TOTALS	-3.77E+05	3.78E+04	-5.15E+03	3.85E+07	-6.32E+08	5.07E+08		TOTALS	-3.77E+05	-3.78E+04	5.15E+03	3.85E+07	6.32E+08	-5.07E+08	1	-1	-1	1	-1	-1
4201	FX	3.04E-01	----	----	----	2.98E+08	6.23E-08	4201	FX	3.04E-01	----	----	----	-2.98E+08	-6.23E-08	1	1	1	1	-1	-1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	-5.32E-01	3.22E-08	-6.71E+08	----		FZ	----	----	5.32E-01	3.22E-08	6.71E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	3.73E+08	----		MY	----	----	----	----	-3.73E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	3.04E-01	0.00E+00	-5.32E-01	3.22E-08	-3.24E+05	6.23E-08		TOTALS	3.04E-01	0.00E+00	5.32E-01	3.22E-08	3.24E+05	-6.23E-08	1	1	-1	1	-1	-1
4202	FX	-1.48E+01	----	----	----	-2.25E+08	1.63E-07	4202	FX	-1.48E+01	----	----	----	2.25E+08	-1.63E-07	1	1	1	1	-1	-1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	1.16E+01	4.66E-10	-2.84E+08	----		FZ	----	----	-1.16E+01	4.66E-10	2.84E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	5.09E+08	----		MY	----	----	----	----	-5.09E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-1.48E+01	0.00E+00	1.16E+01	4.66E-10	4.50E+04	1.63E-07		TOTALS	-1.48E+01	0.00E+00	-1.16E+01	4.66E-10	-4.50E+04	-1.63E-07	1	1	-1	1	-1	-1
4203	FX	-3.05E-01	----	----	----	3.06E+08	2.37E-07	4203	FX	-3.05E-01	----	----	----	-3.06E+08	-2.37E-07	1	1	1	1	-1	-1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	-1.70E+01	3.14E-08	-6.86E+08	----		FZ	----	----	1.70E+01	3.14E-08	6.86E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	3.80E+08	----		MY	----	----	----	----	-3.80E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-3.05E-01	0.00E+00	-1.70E+01	3.14E-08	-3.22E+05	2.37E-07		TOTALS	-3.05E-01	0.00E+00	1.70E+01	3.14E-08	3.22E+05	-2.37E-07	1	1	-1	1	-1	-1
4204	FX	-1.53E+01	----	----	----	-2.20E+08	-7.30E-08	4204	FX	-1.53E+01	----	----	----	2.20E+08	7.30E-08	1	1	1	1	-1	-1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	1.16E+01	5.37E-08	-2.86E+08	----		FZ	----	----	-1.16E+01	5.37E-08	2.86E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	5.07E+08	----		MY	----	----	----	----	-5.07E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-1.53E+01	0.00E+00	1.16E+01	5.37E-08	3.59E+05	-7.30E-08		TOTALS	-1.53E+01	0.00E+00	-1.16E+01	5.37E-08	-3.59E+05	7.30E-08	1	1	-1	1	-1	-1
4205	FX	2.94E-03	----	----	----	2.95E+08	-1.17E-07	4205	FX	2.94E-03	----	----	----	-2.95E+08	1.17E-07	1	1	1	1	-1	-1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	-1.86E+00	-1.70E-08	-6.61E+08	----		FZ	----	----	1.86E+00	-1.70E-08	6.61E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	3.66E+08	----		MY	----	----	----	----	-3.66E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	2.94E-03	0.00E+00	-1.86E+00	-1.70E-08	-2.84E+05	-1.17E-07		TOTALS	2.94E-03	0.00E+00	1.86E+00	-1.70E-08	2.84E+05	1.17E-07	1	1	-1	1	-1	-1
4206	FX	1.50E+01	----	----	----	-2.19E+08	7.10E-08	4206	FX	1.50E+01	----	----	----	2.19E+08	-7.10E-08	1	1	1	1	-1	-1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	4.24E+01	-3.49E-10	-3.02E+08	----		FZ	----	----	-4.24E+01	-3.49E-10	3.02E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	5.20E+08	----		MY	----	----	----	----	-5.20E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	1.50E+01	0.00E+00	4.24E+01	-3.49E-10	-5.55E+05	7.10E-08		TOTALS	1.50E+01	0.00E+00	-4.24E+01	-3.49E-10	5.55E+05	-7.10E-08	1	1	-1	1	-1	-1
4207	FX	-1.50E+01	----	----	----	3.03E+08	3.00E-07	4207	FX	-1.50E+01	----	----	----	-3.03E+08	-3.00E-07	1	1	1	1	-1	-1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	-1.88E+00	3.27E-08	-6.78E+08	----		FZ	----	----	1.88E+00	3.27E-08	6.78E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	3.75E+08	----		MY	----	----	----	----	-3.75E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-1.50E+01	0.00E+00	-1.88E+00	3.27E-08	-1.54E+05	3.00E-07		TOTALS	-1.50E+01	0.00E+00	1.88E+00	3.27E-08	1.54E+05	-3.00E-07	1	1	-1	1	-1	-1
4208	FX	-1.54E-01	----	----	----	-2.11E+08	7.77E-09	4208	FX	-1.54E-01	----	----	----	2.11E+08	-7.77E-09	1	1	1	1	-1	-1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	2.66E+01	-1.71E-08	-3.12E+08	----		FZ	----	----	-2.66E+01	-1.71E-08	3.12E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	5.24E+08	----		MY	----	----	----	----	-5.24E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-1.54E-01	0.00E+00	2.66E+01	-1.71E-08	4.10E+05	7.77E-09		TOTALS	-1.54E-01	0.00E+00	-2.66E+01	-1.71E-08	-4.10E+05	-7.77E-09	1	1	-1	1	-1	-1
4299	FX	-3.97E+04	----	----	----	7.59E+06	5.34E+08	4299	FX	-3.97E+04	----	----	----	-7.59E+06	-5.34E+08	1	1	1	1	-1	-1
	FY	----	1.44E+01	----	2.75E+08	----	-5.47E+08		FY	----	-1.44E+01	----	2.75E+08	----	5.47E+08	1	-1	1	1	1	-1
	FZ	----	----	1.04E+00	3.60E+08	-5.97E+08	----		FZ	----	----	-1.04E+00	3.60E+08	5.97E+08	----	1	1	-1	1	-1	1
	MX	----	----	----	-6.65E+08	----	----		MX	----	----	----	-6.65E+08	----	----	1	1	1	1	1	1
	MY	----	----	----	----	5.64E+08	----		MY	----	----	----	----	-5.64E+08	----	1	1	1	1	-1	1
	MZ	----	----	----	----	----	1.23E+07		MZ	----	----	----	----	----	-1.23E+07	1	1	1	1	1	-1
	TOTALS	-3.97E+04	1.44E+01	1.04E+00	-2.98E+07	-2.53E+07	-6.69E+05		TOTALS	-3.97E+04	-1.44E+01	-1.04E+00	-2.98E+07	2.53E+07	6.69E+05	1	-1	-1	1	-1	-1

Table 6:C-27J Global FEM – OLOAD comparison for inverted model + beam sections vs. v.3.0

	File:	run_static_fusol_jca_ult_dstg							File:	run_static_fusol_jca_ult_dstg						Comparison					
	Version:	3.0	(inverted, beam section + pressure correction)						Version:	Inverted + beam sections						Ti' = Ti(v2.0) / Ti(inverted)					
	OLOAD	RESULTANT							OLOAD	RESULTANT											
SUBCASE	LOAD							SUBCASE	LOAD												
ID	TYPE	T1	T2	T3	R1	R2	R3	ID	TYPE	T1	T2	T3	R1	R2	R3	T1	T2	T3	R1	R2	R3
10	FX	-4.50E+05	----	----	----	1.19E+09	1.11E+08	10	FX	-4.50E+05	----	----	----	1.19E+09	1.11E+08	1	1	1	1	1	1
	FY	----	-5.04E+04	----	8.62E+07	----	-7.87E+08		FY	----	-5.04E+04	----	8.62E+07	----	-7.87E+08	1	1	1	1	1	1
	FZ	----	----	6.79E+03	4.80E+06	-3.75E+08	----		FZ	----	----	6.79E+03	4.80E+06	-3.75E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	0.00E+00	----		MY	----	----	----	----	0.00E+00	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-4.50E+05	-5.04E+04	6.79E+03	9.10E+07	8.10E+08	-6.77E+08		TOTALS	-4.50E+05	-5.04E+04	6.79E+03	9.10E+07	8.10E+08	-6.77E+08	1	1	1	1	1	1
11	FX	-3.77E+05	----	----	----	8.81E+08	-4.51E+08	11	FX	-3.77E+05	----	----	----	8.81E+08	-4.51E+08	1	1	1	1	1	1
	FY	----	-3.78E+04	----	3.40E+08	----	-4.39E+07		FY	----	-3.78E+04	----	3.40E+08	----	-4.39E+07	1	1	1	1	1	1
	FZ	----	----	5.15E+03	3.64E+08	3.15E+08	----		FZ	----	----	5.15E+03	3.64E+08	3.15E+08	----	1	1	1	1	1	1
	MX	----	----	----	-6.65E+08	----	----		MX	----	----	----	-6.65E+08	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-5.64E+08	----		MY	----	----	----	----	-5.64E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	-1.23E+07		MZ	----	----	----	----	----	-1.23E+07	1	1	1	1	1	1
	TOTALS	-3.77E+05	-3.78E+04	5.15E+03	3.85E+07	6.32E+08	-5.07E+08		TOTALS	-3.77E+05	-3.78E+04	5.15E+03	3.85E+07	6.32E+08	-5.07E+08	1	1	1	1	1	1
4201	FX	3.04E-01	----	----	----	-2.98E+08	-6.23E-08	4201	FX	3.04E-01	----	----	----	-2.98E+08	-6.23E-08	1	1	1	1	1	1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	5.32E-01	3.22E-08	6.71E+08	----		FZ	----	----	5.32E-01	3.22E-08	6.71E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-3.73E+08	----		MY	----	----	----	----	-3.73E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	3.04E-01	0.00E+00	5.32E-01	3.22E-08	3.24E+05	-6.23E-08		TOTALS	3.04E-01	0.00E+00	5.32E-01	3.22E-08	3.24E+05	-6.23E-08	1	1	1	1	1	1
4202	FX	-1.48E+01	----	----	----	2.25E+08	-1.63E-07	4202	FX	-1.48E+01	----	----	----	2.25E+08	-1.63E-07	1	1	1	1	1	1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	-1.16E+01	4.66E-10	2.84E+08	----		FZ	----	----	-1.16E+01	4.66E-10	2.84E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-5.09E+08	----		MY	----	----	----	----	-5.09E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-1.48E+01	0.00E+00	-1.16E+01	4.66E-10	-4.50E+04	-1.63E-07		TOTALS	-1.48E+01	0.00E+00	-1.16E+01	4.66E-10	-4.50E+04	-1.63E-07	1	1	1	1	1	1
4203	FX	-3.05E-01	----	----	----	-3.06E+08	-2.37E-07	4203	FX	-3.05E-01	----	----	----	-3.06E+08	-2.37E-07	1	1	1	1	1	1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	1.70E+01	3.14E-08	6.86E+08	----		FZ	----	----	1.70E+01	3.14E-08	6.86E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-3.80E+08	----		MY	----	----	----	----	-3.80E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-3.05E-01	0.00E+00	1.70E+01	3.14E-08	3.22E+05	-2.37E-07		TOTALS	-3.05E-01	0.00E+00	1.70E+01	3.14E-08	3.22E+05	-2.37E-07	1	1	1	1	1	1
4204	FX	-1.53E+01	----	----	----	2.20E+08	7.30E-08	4204	FX	-1.53E+01	----	----	----	2.20E+08	7.30E-08	1	1	1	1	1	1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	-1.16E+01	5.37E-08	2.86E+08	----		FZ	----	----	-1.16E+01	5.37E-08	2.86E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-5.07E+08	----		MY	----	----	----	----	-5.07E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-1.53E+01	0.00E+00	-1.16E+01	5.37E-08	-3.59E+05	7.30E-08		TOTALS	-1.53E+01	0.00E+00	-1.16E+01	5.37E-08	-3.59E+05	7.30E-08	1	1	1	1	1	1
4205	FX	2.94E-03	----	----	----	-2.95E+08	1.17E-07	4205	FX	2.94E-03	----	----	----	-2.95E+08	1.17E-07	1	1	1	1	1	1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	1.86E+00	-1.70E-08	6.61E+08	----		FZ	----	----	1.86E+00	-1.70E-08	6.61E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-3.66E+08	----		MY	----	----	----	----	-3.66E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	2.94E-03	0.00E+00	1.86E+00	-1.70E-08	2.84E+05	1.17E-07		TOTALS	2.94E-03	0.00E+00	1.86E+00	-1.70E-08	2.84E+05	1.17E-07	1	1	1	1	1	1
4206	FX	1.50E+01	----	----	----	2.19E+08	-7.10E-08	4206	FX	1.50E+01	----	----	----	2.19E+08	-7.10E-08	1	1	1	1	1	1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	-4.24E+01	-3.49E-10	3.02E+08	----		FZ	----	----	-4.24E+01	-3.49E-10	3.02E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-5.20E+08	----		MY	----	----	----	----	-5.20E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	1.50E+01	0.00E+00	-4.24E+01	-3.49E-10	5.55E+05	-7.10E-08		TOTALS	1.50E+01	0.00E+00	-4.24E+01	-3.49E-10	5.55E+05	-7.10E-08	1	1	1	1	1	1
4207	FX	-1.50E+01	----	----	----	-3.03E+08	-3.00E-07	4207	FX	-1.50E+01	----	----	----	-3.03E+08	-3.00E-07	1	1	1	1	1	1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	1.88E+00	3.27E-08	6.78E+08	----		FZ	----	----	1.88E+00	3.27E-08	6.78E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-3.75E+08	----		MY	----	----	----	----	-3.75E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-1.50E+01	0.00E+00	1.88E+00	3.27E-08	1.54E+05	-3.00E-07		TOTALS	-1.50E+01	0.00E+00	1.88E+00	3.27E-08	1.54E+05	-3.00E-07	1	1	1	1	1	1
4208	FX	-1.54E-01	----	----	----	2.11E+08	-7.77E-09	4208	FX	-1.54E-01	----	----	----	2.11E+08	-7.77E-09	1	1	1	1	1	1
	FY	----	0.00E+00	----	0.00E+00	----	0.00E+00		FY	----	0.00E+00	----	0.00E+00	----	0.00E+00	1	1	1	1	1	1
	FZ	----	----	-2.66E+01	-1.71E-08	3.12E+08	----		FZ	----	----	-2.66E+01	-1.71E-08	3.12E+08	----	1	1	1	1	1	1
	MX	----	----	----	0.00E+00	----	----		MX	----	----	----	0.00E+00	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-5.24E+08	----		MY	----	----	----	----	-5.24E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	0.00E+00		MZ	----	----	----	----	----	0.00E+00	1	1	1	1	1	1
	TOTALS	-1.54E-01	0.00E+00	-2.66E+01	-1.71E-08	-4.10E+05	-7.77E-09		TOTALS	-1.54E-01	0.00E+00	-2.66E+01	-1.71E-08	-4.10E+05	-7.77E-09	1	1	1	1	1	1
4299	FX	-3.97E+04	----	----	----	-7.59E+06	-5.34E+08	4299	FX	-3.97E+04	----	----	----	-7.59E+06	-5.34E+08	1	1	1	1	1	1
	FY	----	-1.44E+01	----	2.75E+08	----	5.47E+08		FY	----	-1.44E+01	----	2.75E+08	----	5.47E+08	1	1	1	1	1	1
	FZ	----	----	-1.04E+00	3.60E+08	5.97E+08	----		FZ	----	----	-1.04E+00	3.60E+08	5.97E+08	----	1	1	1	1	1	1
	MX	----	----	----	-6.65E+08	----	----		MX	----	----	----	-6.65E+08	----	----	1	1	1	1	1	1
	MY	----	----	----	----	-5.64E+08	----		MY	----	----	----	----	-5.64E+08	----	1	1	1	1	1	1
	MZ	----	----	----	----	----	-1.23E+07		MZ	----	----	----	----	----	-1.23E+07	1	1	1	1	1	1
	TOTALS	-3.97E+04	-1.44E+01	-1.04E+00	-2.98E+07	2.53E+07	6.69E+05		TOTALS	-3.97E+04	-1.44E+01	-1.04E+00	-2.98E+07	2.53E+07	6.69E+05	1	1	1	1	1	1

Table 7: Description of each component of the DST Group Model Check Results

Item #	Model Check Criteria	Model Check Description
1	Mass (tonne)	Reports the FEM mass from the Nastran f06 file. This is compared to any user supplied expected value and will highlight any unexpected changes to the mass when incorporating modifications to the model.
2	CG (mm)	Reports the FEM Centre-of-Gravity (CG) from the Nastran f06 file. This is compared to any user supplied expected value and will highlight any unexpected changes to the CG when incorporating modifications to the model.
3	Maximum Displacement for Unit Acceleration (mm)	Reports the maximum FEM displacements produced by unit acceleration from the Nastran f06 file. This is compared to any user supplied expected value
4	Work Error (Epsilon) Check	Provides a measure of the numerical accuracy of the model. The error is a ratio of the work done by the residual forces to the work done by the applied forces [2]. MSC (the developer of Nastran) recommend epsilon values of less than 1.0E-9 as per [8].
5	Load Equilibrium Check	Compares output from the Nastran GPWG to the SPCFORCE and OLOADS resultants. Provides a measure of equality of weight, applied force and the reaction force under 1G or unit acceleration loading. For an error free model, the output from the three sources should be identical [2](i.e. zero percentage difference).
6	Rigid Body Residual Strain Energy Check	Reports the rigid body strain energy check results from applying unit translational and rotational displacements to identify any unintentional constraints. This can identify possible source and nature of modelling errors.
7	Free-Free Normal Modes Check	Reports the results of the free-free normal modes check to verify that no artificial grounding effects show up in the dynamic analysis. The ratio of the first flexural mode to the highest rigid body modal frequency should be more than 1.0E5.

Figures

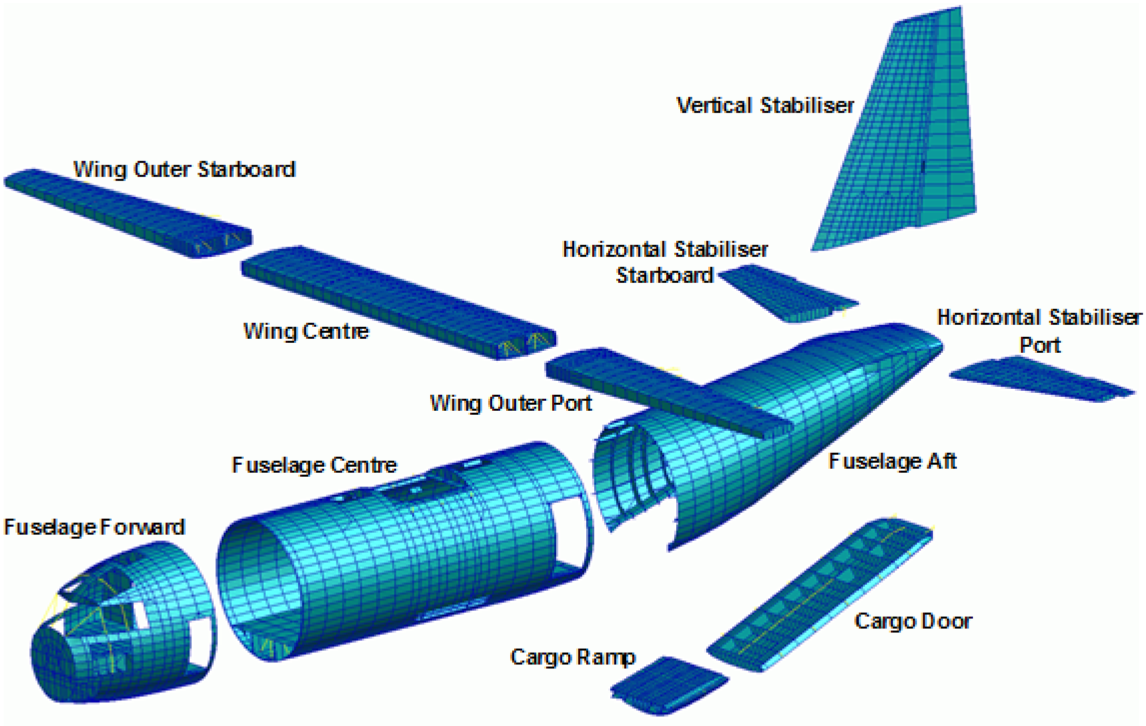


Figure 1: Submodels of the C-27J global FEM

v1.0

- ☑ separate global model into independent submodels representative of each substructure
- ☑ convert all membrane and shear elements to shell elements
- ☑ convert all rod elements to bar elements
- ☑ create RBE2 rigid body elements to connect submodels together
- ☑ create a single file for all material properties
- ☑ create a single file for all coordinate systems
- ☑ remove all Mulitpoint Constraint entries (MPC)

v2.0

- ☑ renumber all entities in FEM according to define numbering ranges
- ☑ create grid and element id maps for Alenia ids to DSTG ids
- ☑ consolidate all duplicate material property entries (74) to as few as possible (3)
- ☑ create N/Mpa version of material property file as well as the original daN/daMPa
- ☑ convert force and moment units from daN to N and daN-m to N-m respectively
- ☑ convert all bulk data file names to English

v3.0

- ☑ flip model in Z
- ☑ flip load files in Z
- ☑ incorporate PBMSECT properties
- ☑ apply consistent unit system (N, mm, degC)

Figure 2: Completed FEM enhancements and verification activities for versions 1 to 3

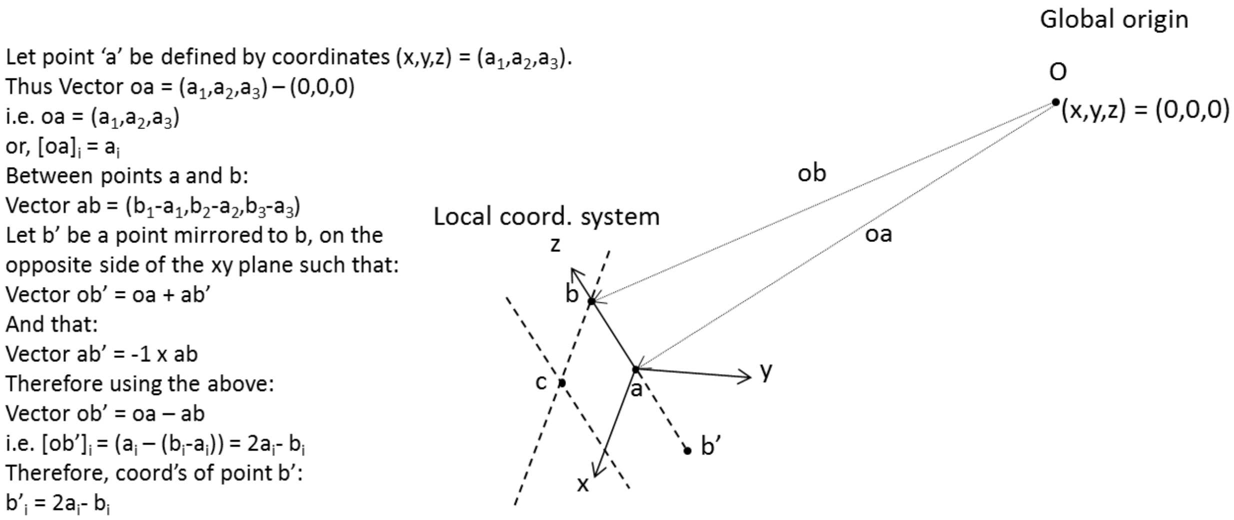


Figure 3: Derivation of coordinate transformation terms for inverting local coordinate systems

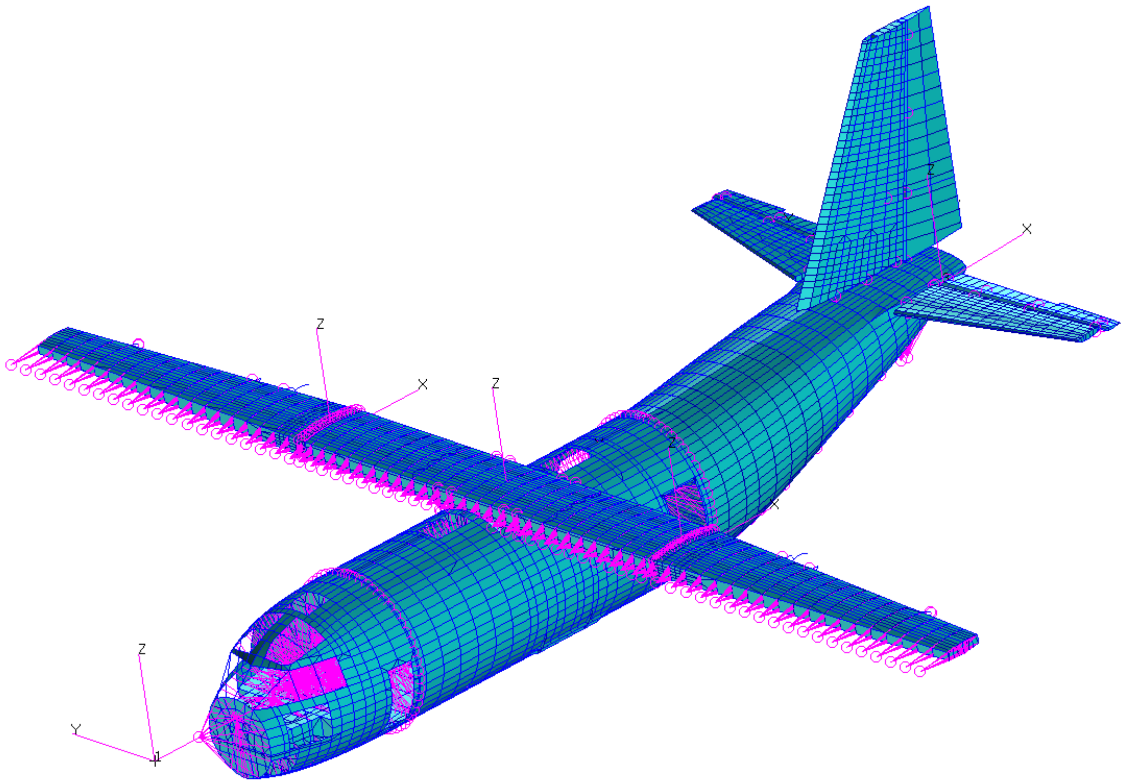


Figure 4: Enhanced C-27J global finite element model showing the interface and loading RBE’s. Several coordinate systems are shown, illustrating the inverted state of the model.

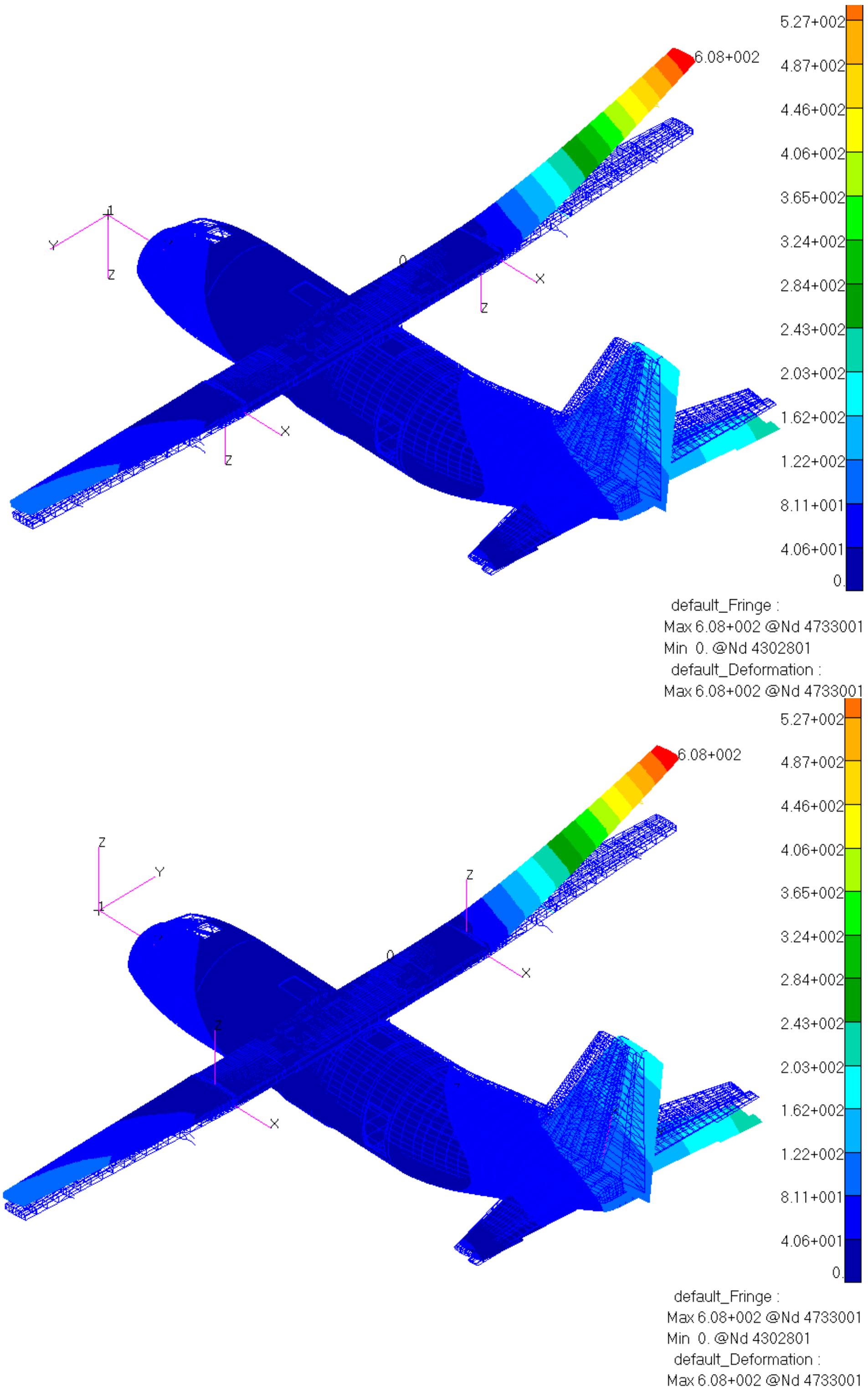


Figure 5: C-27J Global FEM – model displacement response comparison; load case 4299 (left lateral manoeuvre envelope). Top: v2.0. Bottom: spatially inverted (units: mm).

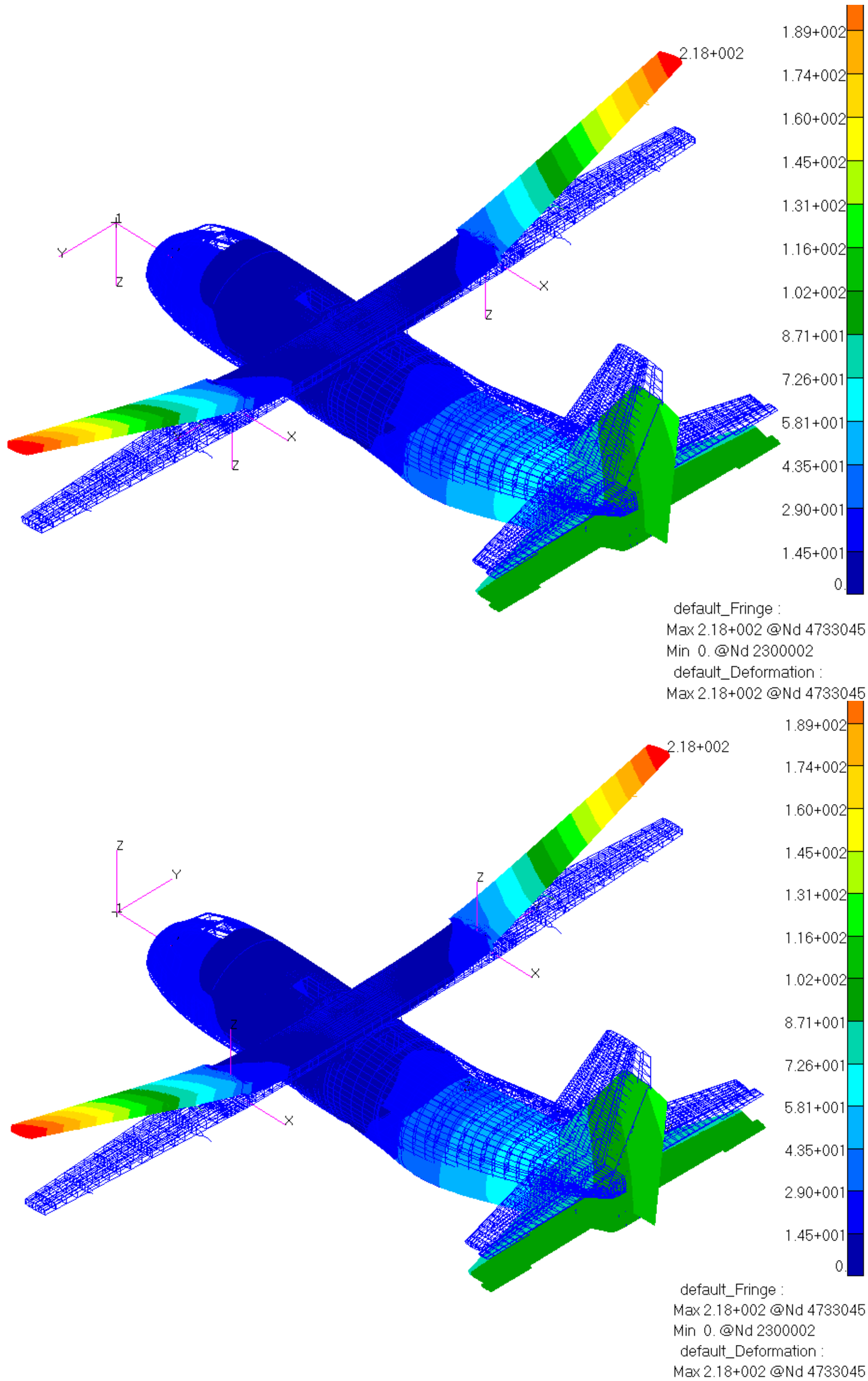


Figure 6: C-27J Global FEM – model displacement response comparison; load case 4203 (spin up at M2_C). Top: v2.0. Bottom: spatially inverted (units: mm).

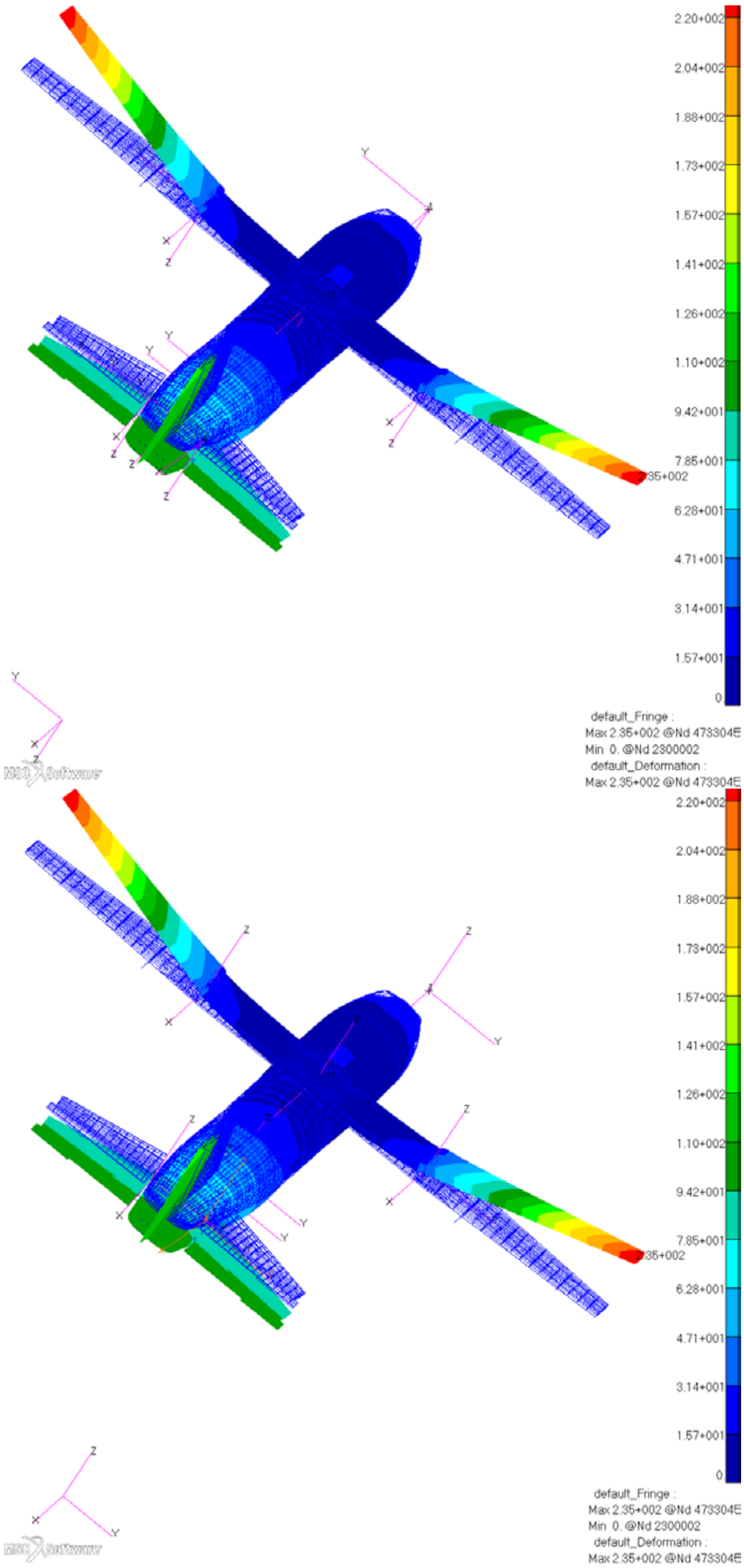


Figure 7: C-27J Global FEM – model displacement response comparison; load case 4201 (spin up at M_2B). Top: v2.0. Bottom: spatially inverted (units: mm).

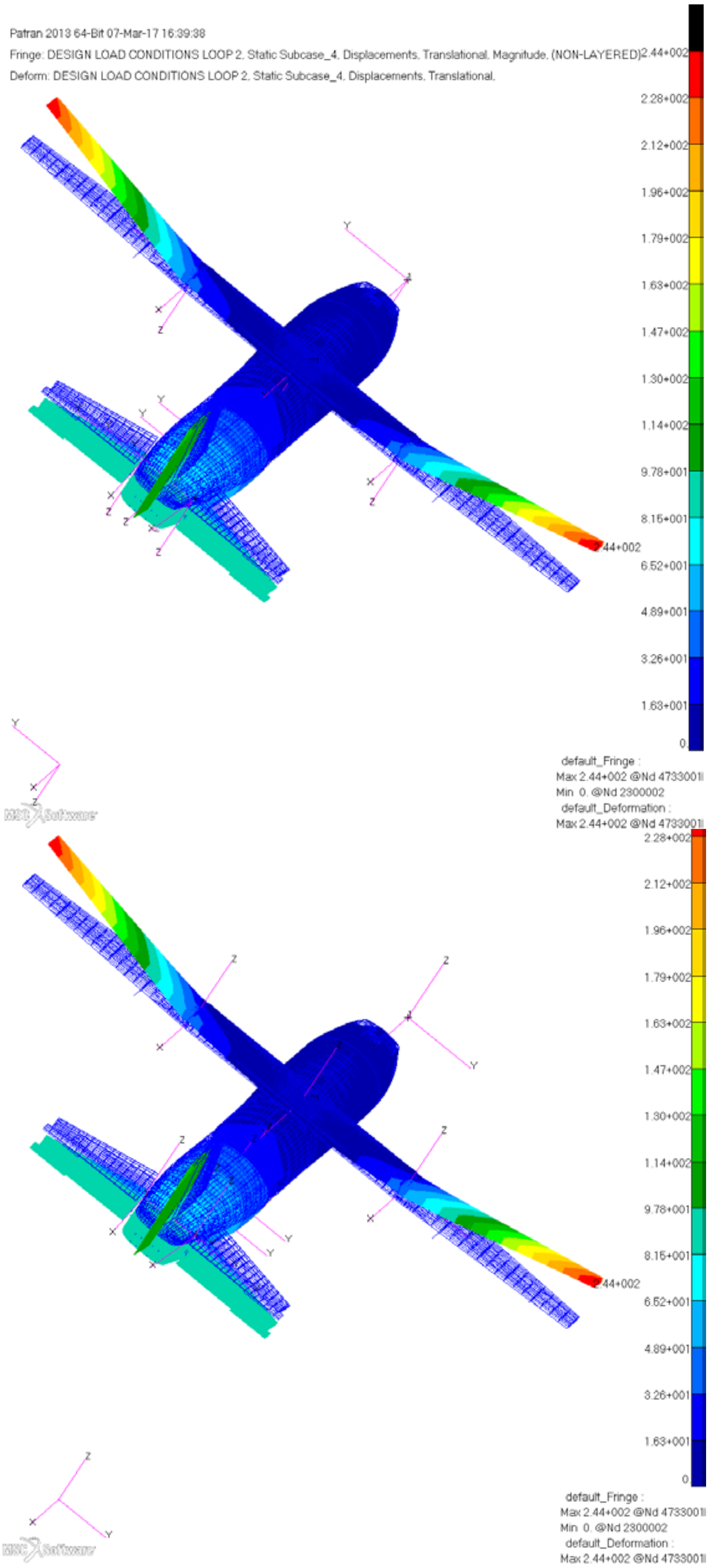


Figure 8: C-27J Global FEM – inverted model displacement response comparison; load case 4202 (spring back at M2_B). Top: v2.0. Bottom: spatially inverted (units: mm).

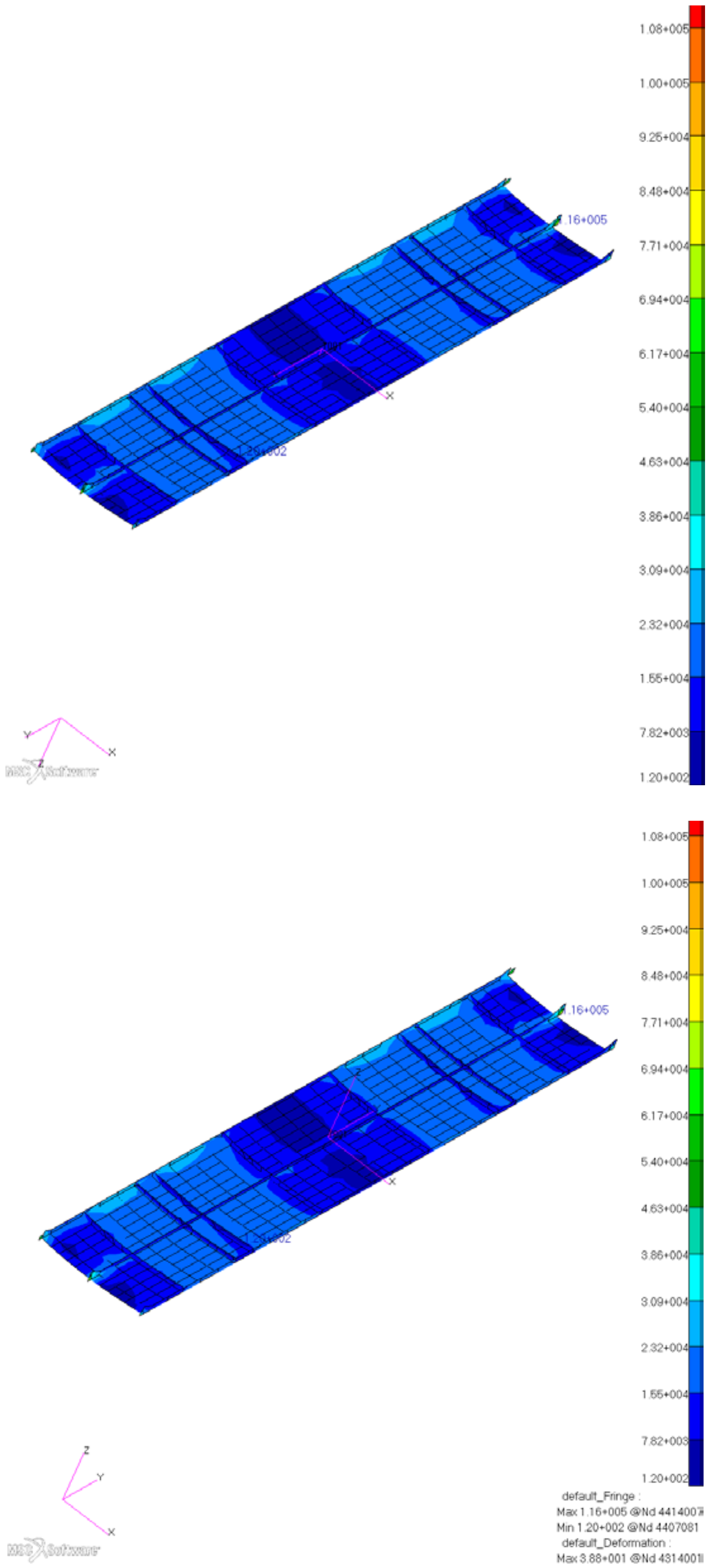


Figure 9: C-27J Global FEM – model response comparison; load case 4208 (spring back at M2_E), Centre Wingbox, Cover, Lower; grid point internal forces (units: N). Top: v2.0, Bottom: v3.0

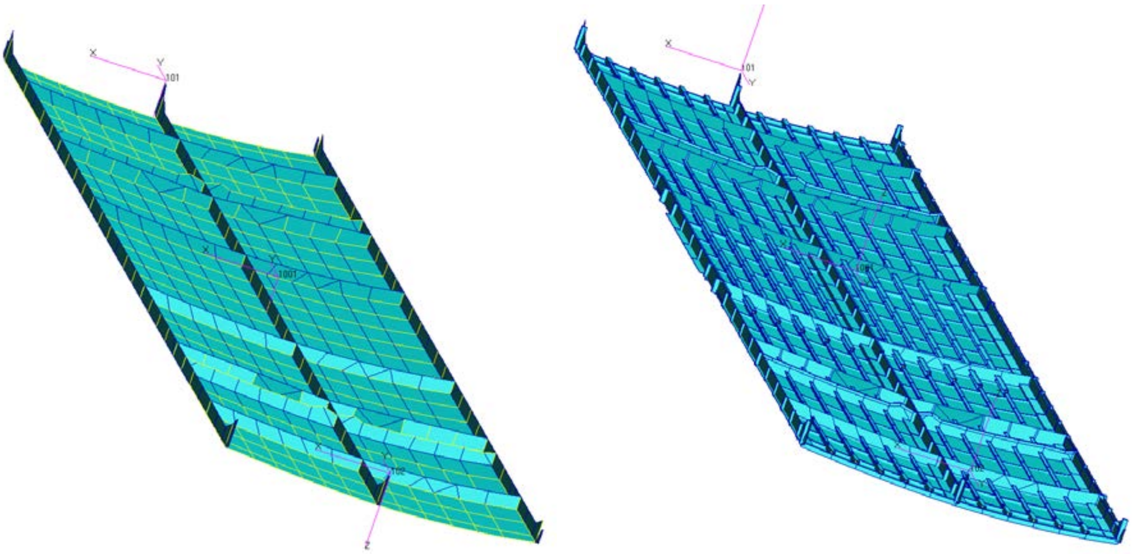


Figure 10: C-27J Global FEM – Centre wingbox lower cover (v2.0 left, v3.0 right)

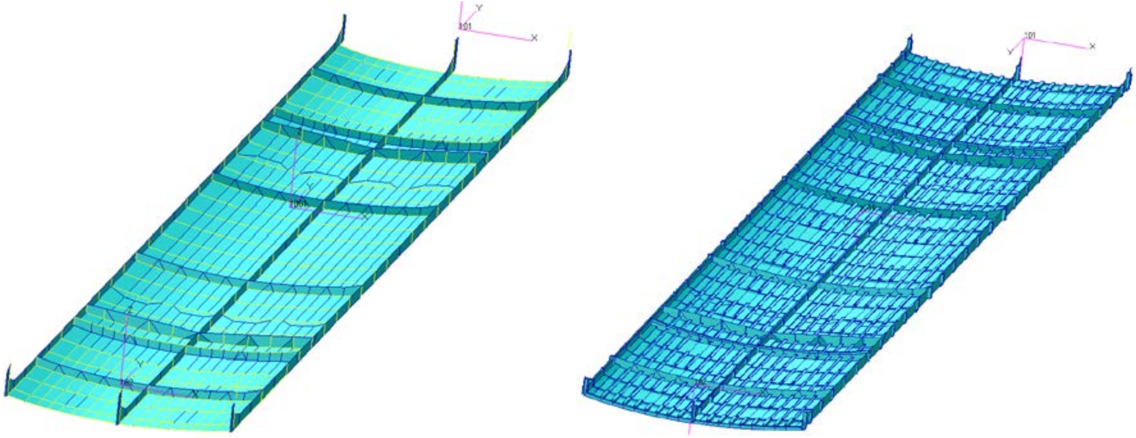


Figure 11: C-27J Global FEM – Centre wingbox upper cover (v2.0 left, v3.0 right)

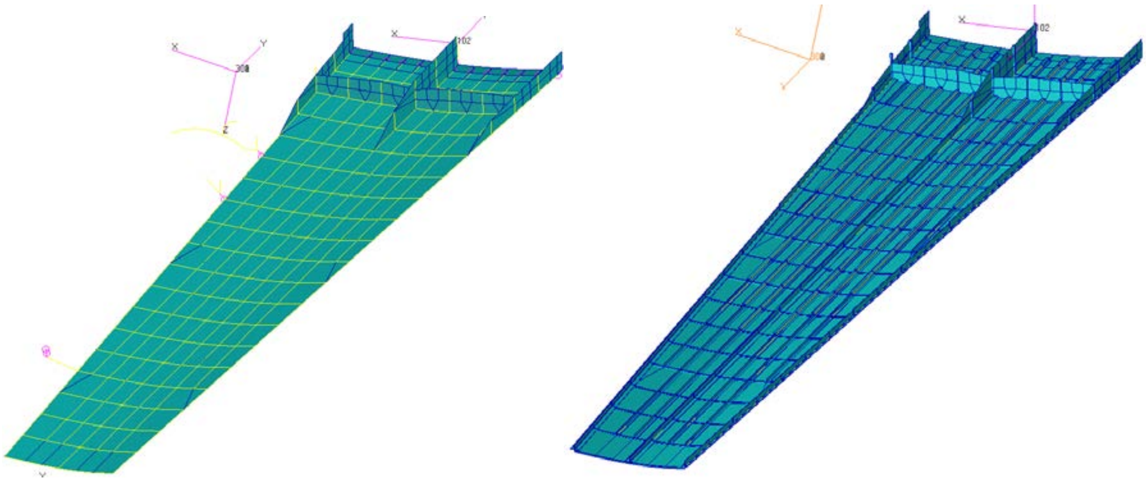


Figure 12: C-27J Global FEM – wing outer cover, lower, starboard (v2.0 left, v3.0 right)

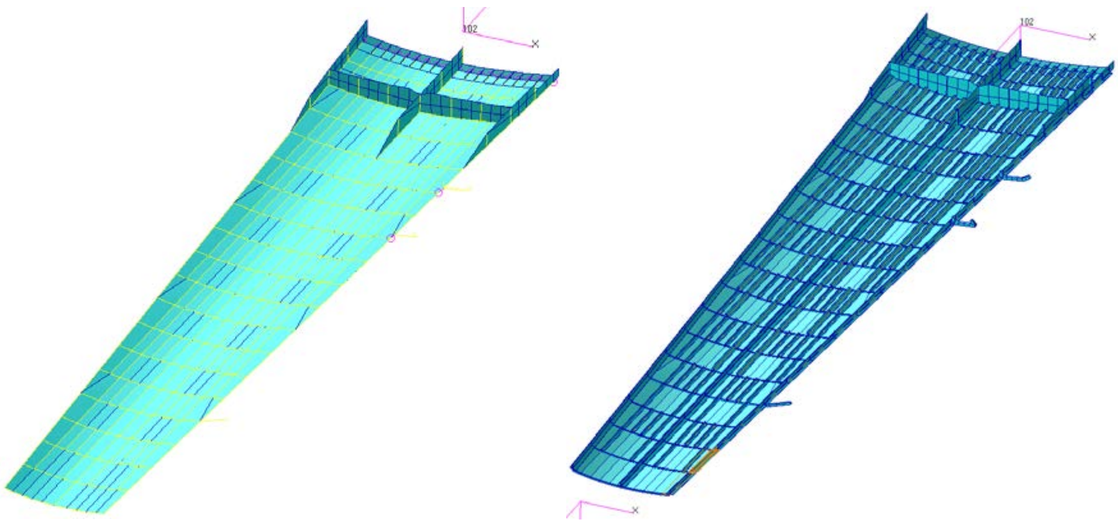


Figure 13: C-27J Global FEM – wing outer cover, upper, starboard (v2.0 left, v3.0 right)

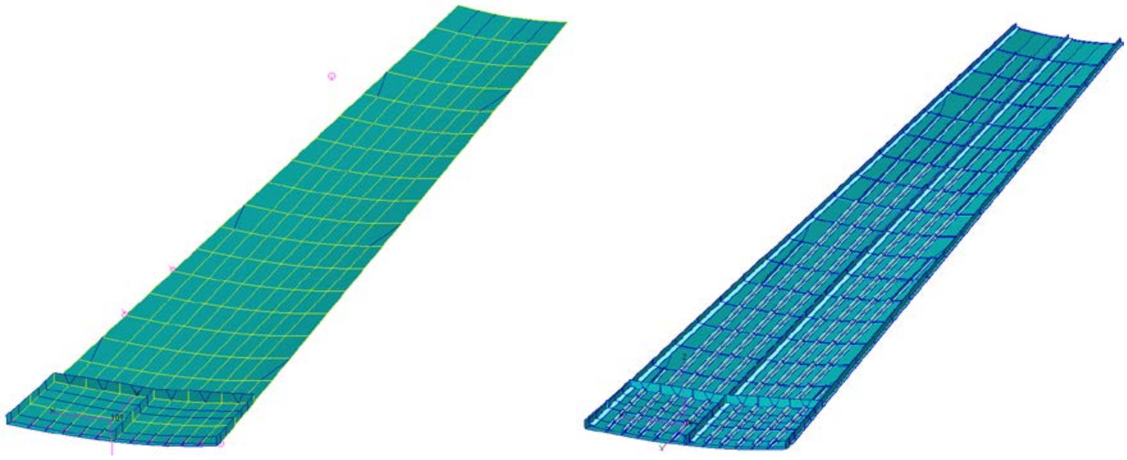


Figure 14: C-27J Global FEM – wing outer cover, lower, port (v2.0 left, v3.0 right)

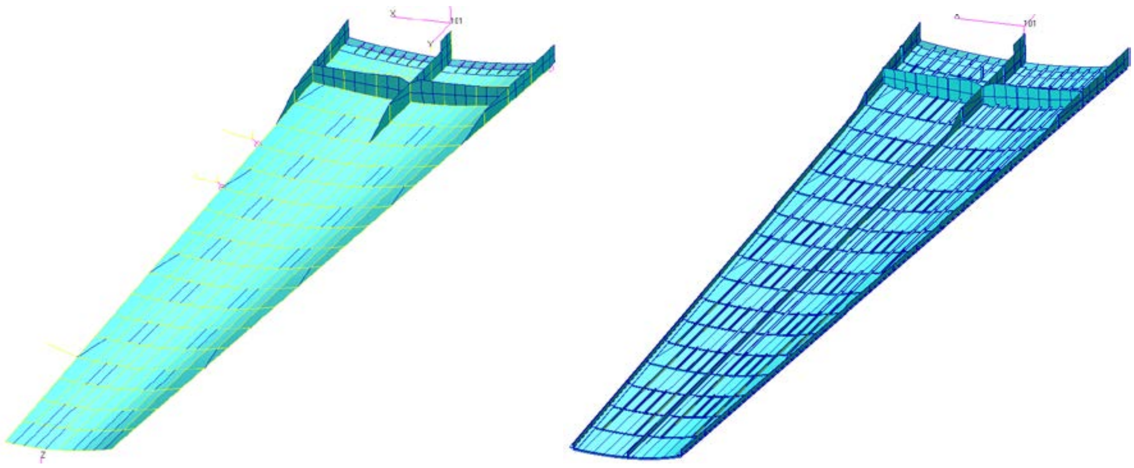


Figure 15: C-27J Global FEM – wing outer cover, upper, port (v2.0 left, v3.0 right

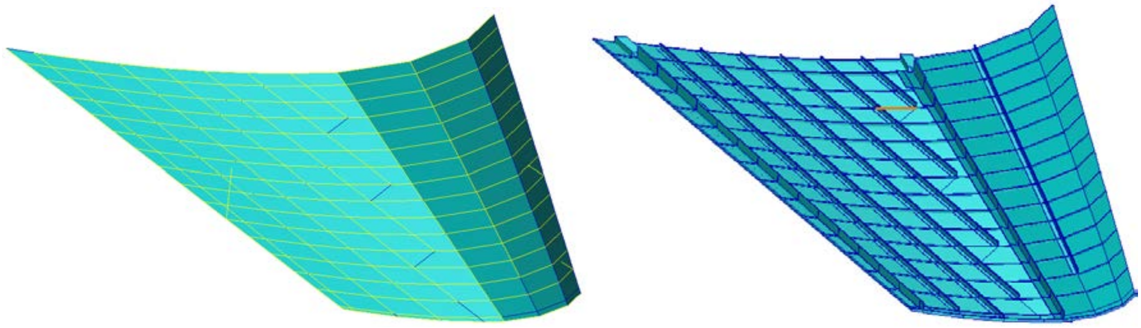


Figure 16: C-27J Global FEM – horizontal stabiliser cover, lower, starboard (v2.0 left, v3.0 right)

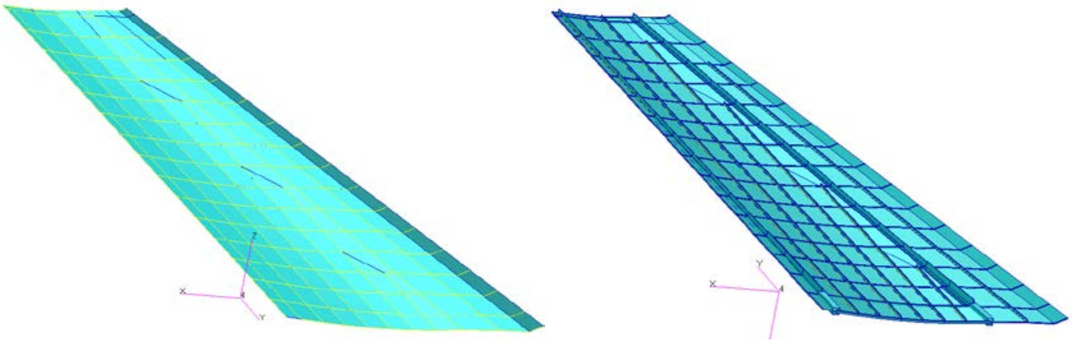


Figure 17: C-27J Global FEM – horizontal stabiliser cover, upper, starboard (v2.0 left, v3.0 right)

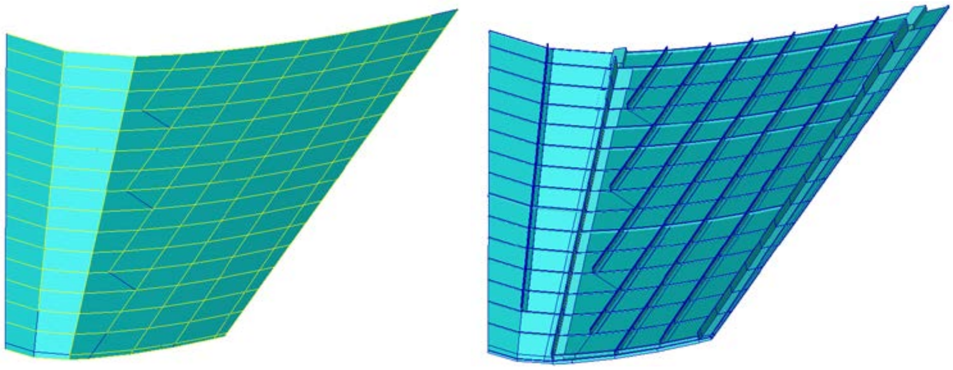


Figure 18: C-27J Global FEM – horizontal stabiliser cover, lower, port (v2.0 left, v3.0 right)

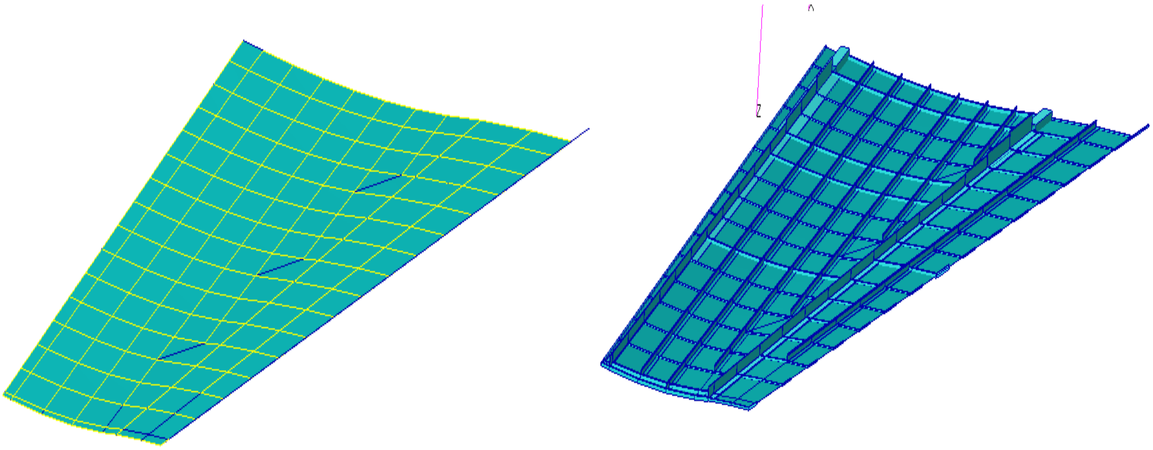


Figure 19: C-27J Global FEM – horizontal stabiliser cover, upper, port (v2.0 left, v3.0 right)

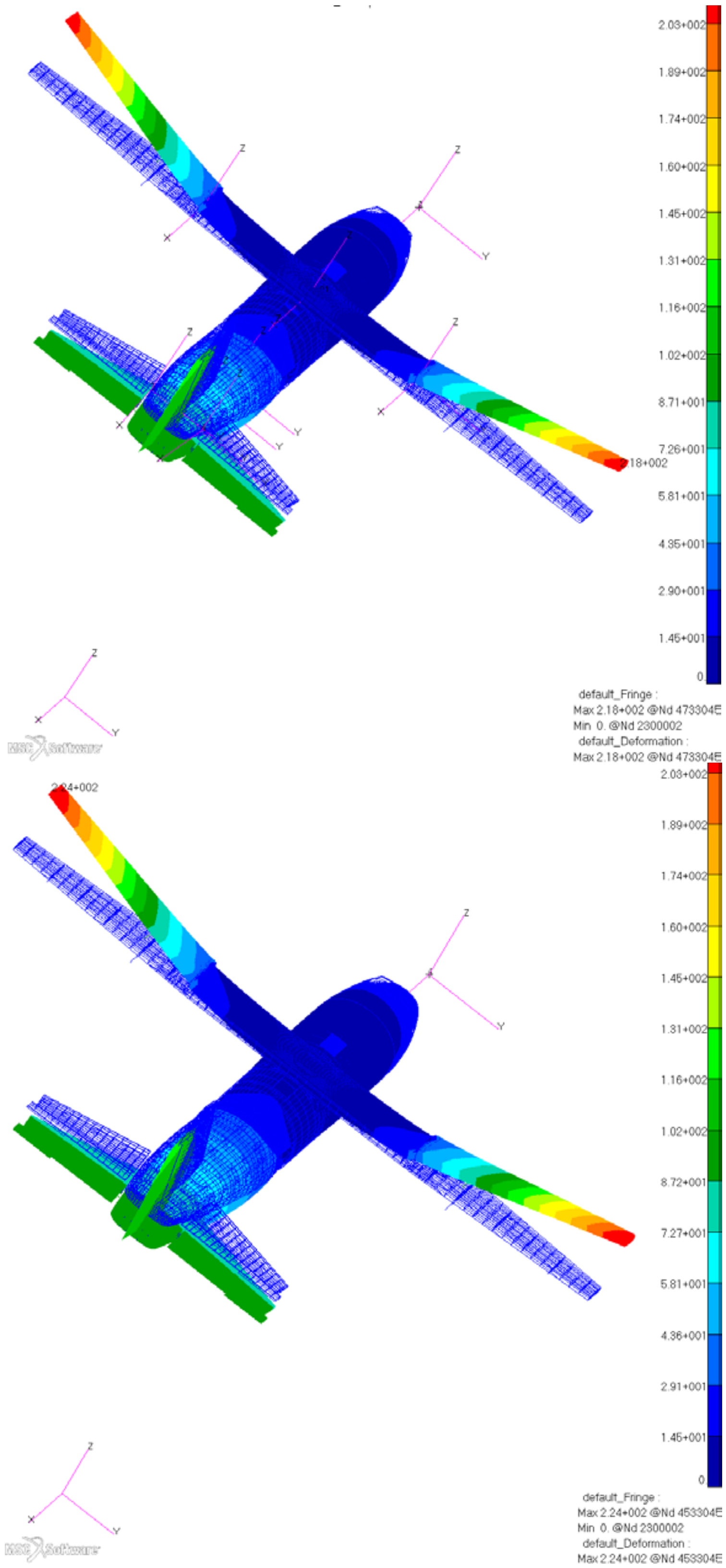


Figure 20: C-27J Global FEM – model displacement response comparison; load case 4203 (spin up at M2_C). Top: spatially inverted. Bottom: v3.0 (units: mm).

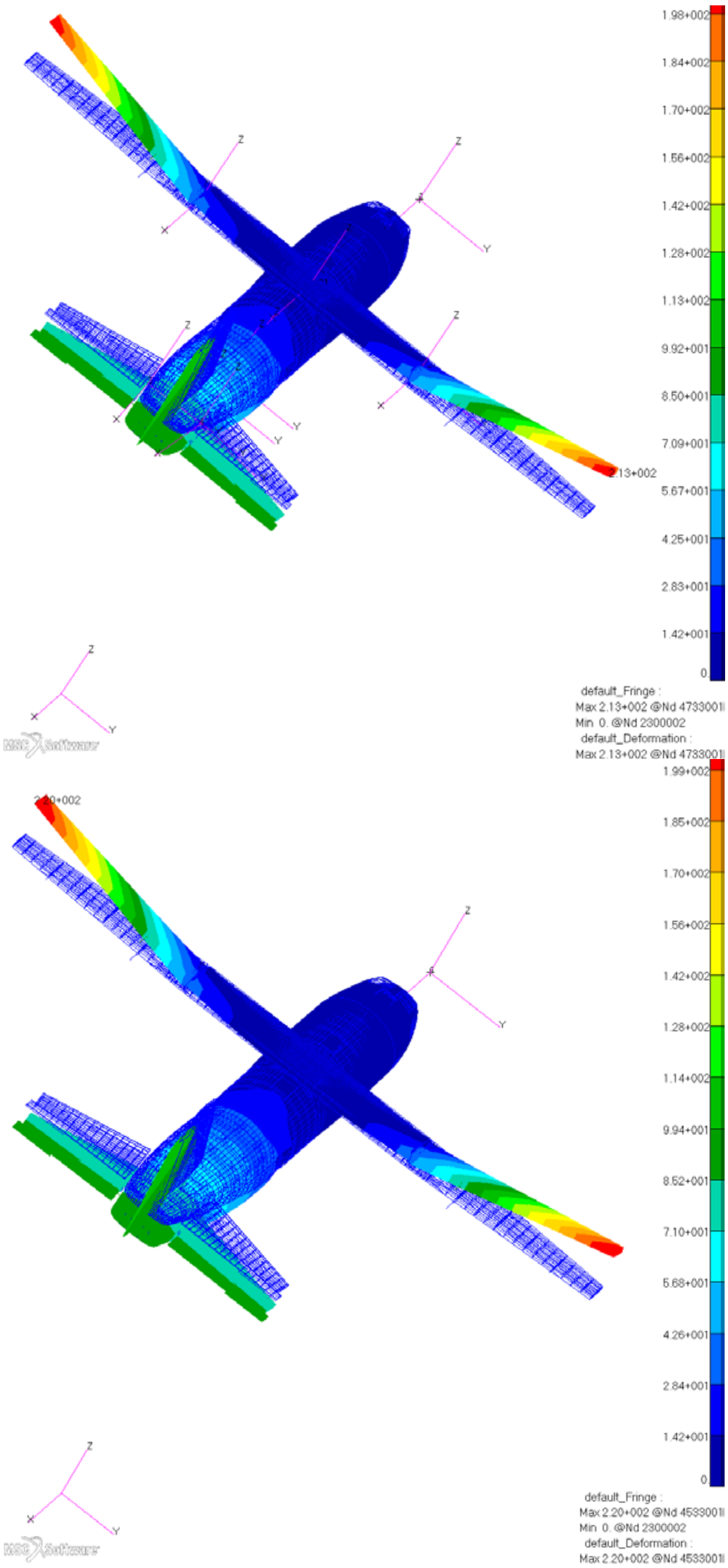


Figure 21: C-27J Global FEM – model displacement response comparison; load case 4204 (spring back at M2_C). Top: spatially inverted. Bottom: v3.0 (units: mm).

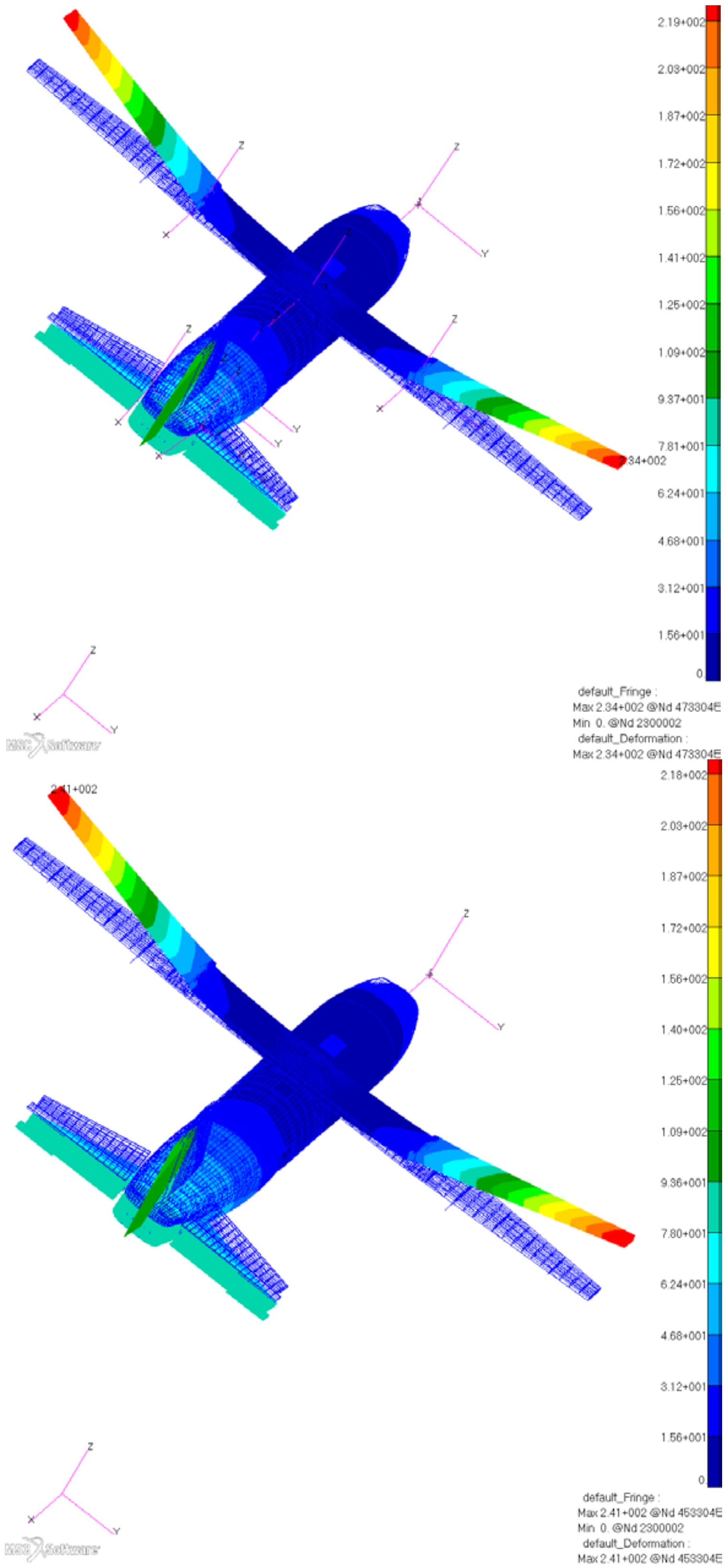


Figure 22: C-27J Global FEM – model displacement response comparison; load case 4205 (spin up at M2_D). Top: spatially inverted. Bottom: v3.0 (units: mm).

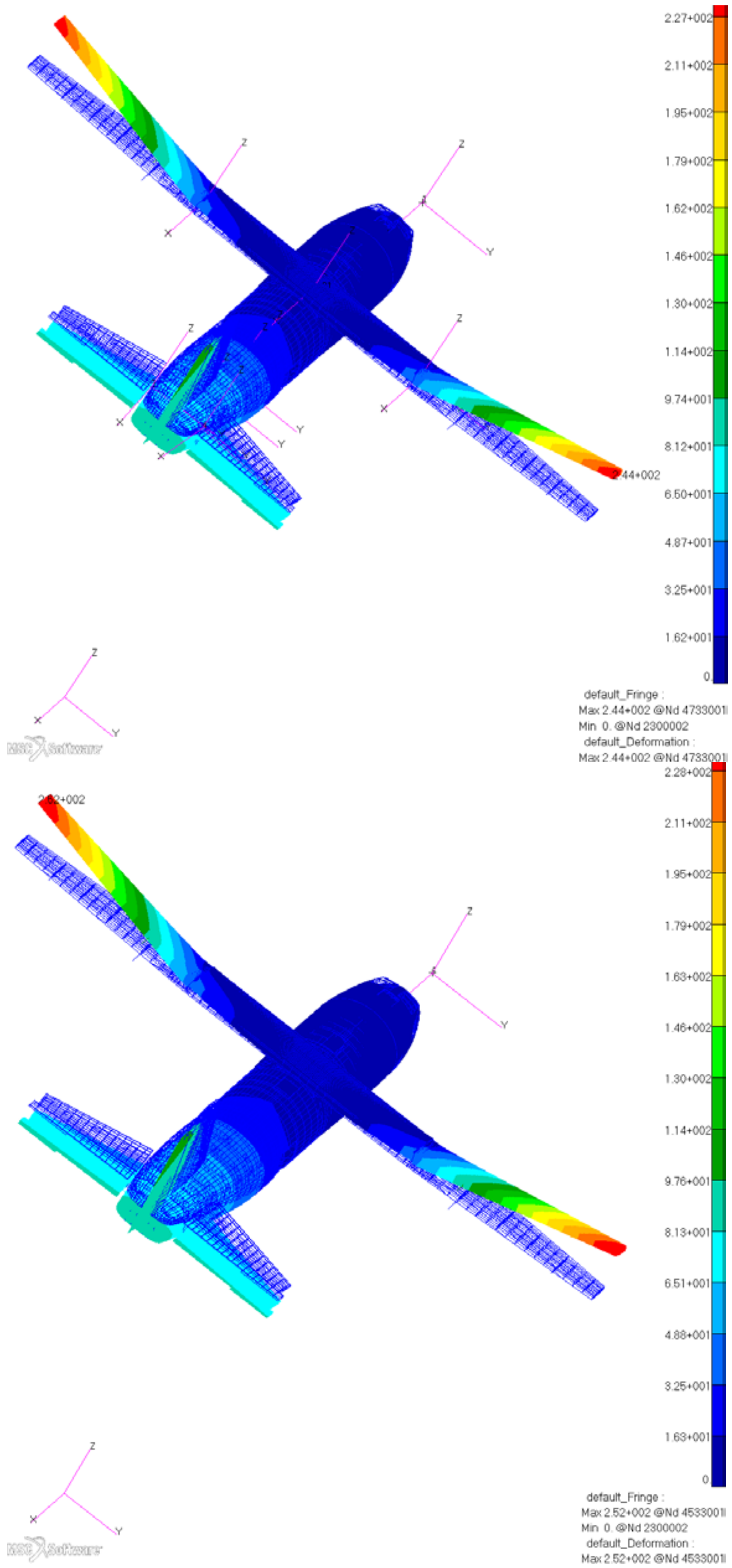
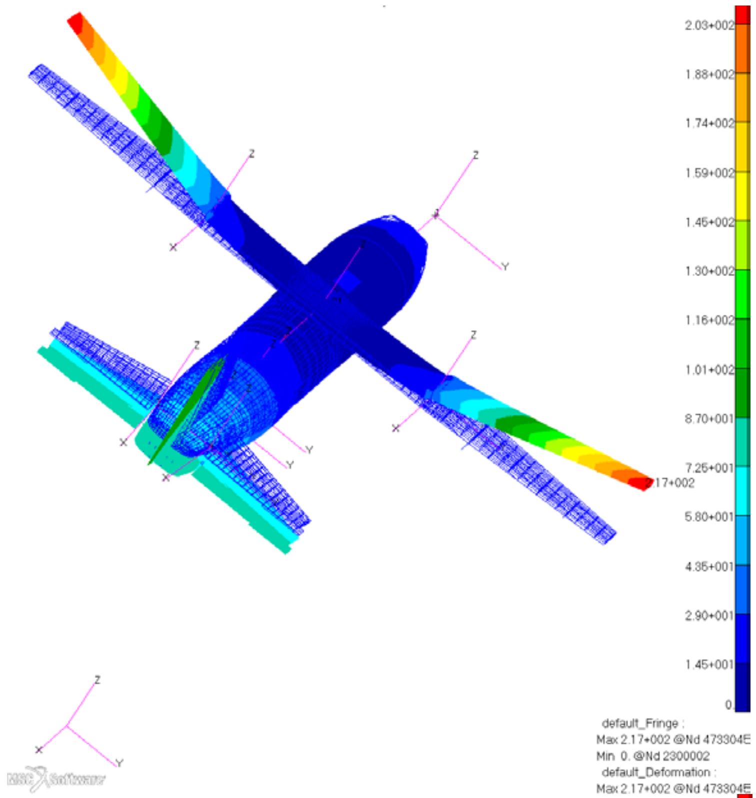


Figure 23: C-27J Global FEM – model displacement response comparison; load case 4206 (spring back at M2_D). Top: spatially inverted. Bottom: v3.0 (units: mm).



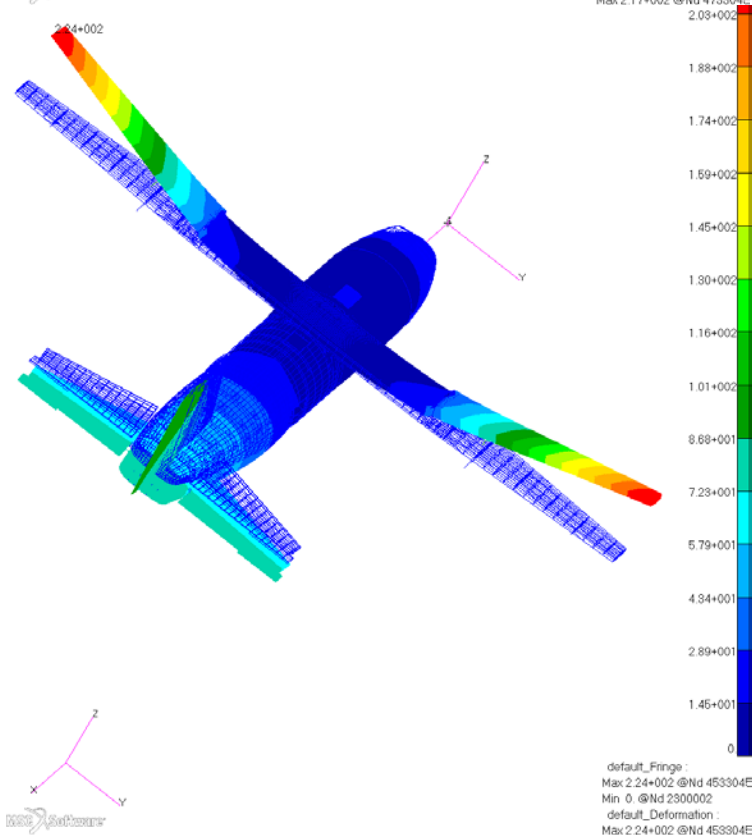


Figure 24: C-27J Global FEM – model displacement response comparison; load case 4207 (spin up at M2_E). Top: spatially inverted. Bottom: v3.0 (units: mm).

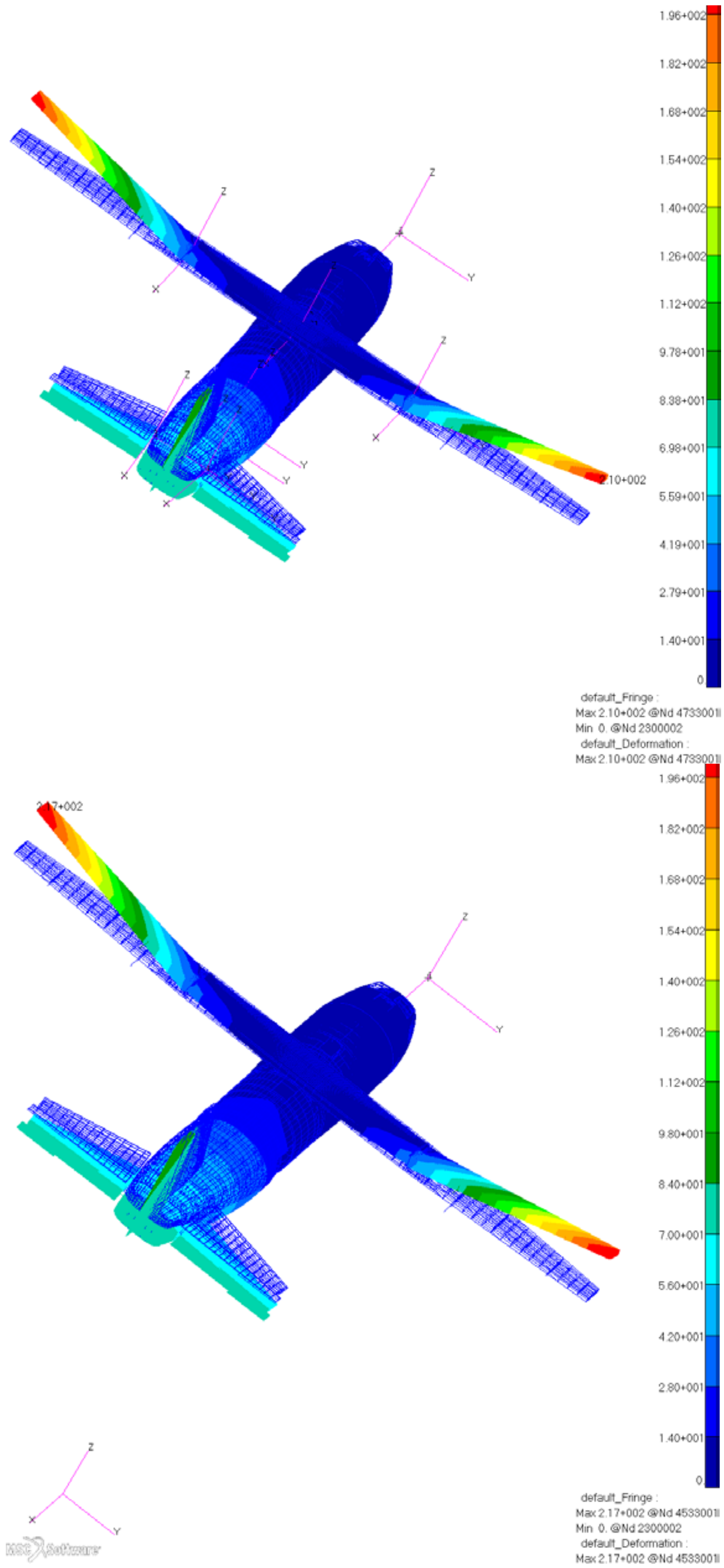


Figure 25: C-27J Global FEM – model displacement response comparison; load case 4208 (spring back at M2_E). Top: spatially inverted. Bottom: v3.0 (units: mm).

Mass (kg)

	FEM	Expected	Difference			
Total	4.910873E+03	4.941019E+03	3.014600E+01	0.61%		FAIL
					1%	WARNING
					0.01%	PASS

CG (mm)

	FEM	Expected	Difference			
X	1.241842E+04	1.241100E+04	-7.420000E+00	-0.06%		FAIL
Y	3.141352E-01	4.661260E-01	1.519908E-01	32.61%	1%	WARNING
Z	8.191487E+02	8.263597E+02	7.211000E+00	0.87%	0.01%	PASS

Maximum Displacements for Unit Acceleration (mm)

	FEM	Expected	Difference			
X	5.044592E-01	5.095537E-01	5.094470E-03	1.00%		FAIL
Y	1.029011E+00	1.027582E+00	-1.428500E-03	-0.14%	5%	WARNING
Z	2.899953E+00	2.902203E+00	2.250100E-03	0.08%	1.00%	PASS

Work Error (Epsilon) Check

$1 mm/s^2$ in X	-7.22903E-12		FAIL
$1 mm/s^2$ in Y	-3.31411E-11	1.00E-06	WARNING
$1 mm/s^2$ in Z	-8.09318E-12	1.00E-09	PASS

Load Equilibrium Check

$1 mm/s^2$ in X	0.00%		FAIL
$1 mm/s^2$ in Y	0.00%	1%	WARNING
$1 mm/s^2$ in Z	0.00%	0.10%	PASS

Rigid Body Residual Strain Energy Check

		Max S.E.	
G Set	PASS	1.055602E+00	FAIL
N Set	PASS	1.221841E+00	PASS
F Set	PASS	1.221841E+00	
A Set	PASS	1.221841E+00	

Free-Free Normal Modes Check

Mode	Frequency (Hz)	F_7/F_m Ratio (mode=1 to 6)		
1	2.766651E-05	5.028979E+05		FAIL
2	1.224673E-05	1.136093E+06	1.00E+04	WARNING
3	4.725949E-05	2.944050E+05	1.00E+05	PASS
4	7.014770E-05	1.983448E+05		
5	8.182094E-05	1.700473E+05		
6	8.986149E-05	1.548320E+05		
7	1.391343E+01			

Figure 26: Nastran model check results as per Nastran model checking tool.

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19. ABSTRACT

The Royal Australian Air Force (RAAF) has commenced a fleet acquisition of C 27J aircraft (AIR8000 Phase 2) to support RAAF tactical airlift capability requirements. As part of the Structural Substantiation Program, a global Finite Element Model (FEM) of the C 27J airframe was obtained from the Original Equipment Manufacturer, Alenia Aeronautica. A global airframe FEM is an important supplementary tool to aid in support of both current and future RAAF C 27J structural integrity management. In 2013, Defence Science and Technology Group completed a preliminary review of the C 27J global FEM and recommended several areas of model enhancement, including specific C 27J FEM verification and validation activities. The key enhancements are: inversion about the global x-axis for all model and load files, incorporation of beam element section properties representative of design section geometry, and finally, creation of a uniform set of engineering units to be used consistently for the model geometry, model materials, and applied loads. Model verification was carried out following application of each of these enhancements and reported. Pending experimental validation, the enhanced and verified C 27J global FEM, known as "C 27J_GFEM_DSTG-v3.0", is a linear elastic internal loads model that will be useful in providing global loads results such as wing tip displacements, field stresses, running loads, and connection forces.