Technical Report N°1319 - 2015

MR002 Rev. 2 dated 12/11/2015

FEM Analysis of

TMB System

Requested by: Comet Fans s.r.l..

20020 Solaro (Mi), Via Leonardo da Vinci 17

with order n.F1501682 dated 20/10/2015

Cormano Head Office, 03/12/2015

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AUTHOR	**CHECK**	**APPROVAL**

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Appendix 1 Forces acting on the Bolts

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1 Introduction

This work shows the stress analysis of the *TMB System* built by Comet Fans. According to the Customer design requirements, the design will be checked against static and fatigue loads. The verifications were carried out according to the Customer Specification n.383601 Rev.0.

The FE Model of the *TMB System* was built based on the CAD 3D model provided by Comet Fans, last version according to the 2D drawing SC 227 FEA TMB SYSTEM.

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2 Software

The Finite Element Model was prepared and the results were analyzed using MSC Patran 2014 pre/post processor, whereas the analyses were performed using MSC Nastran 2013 code.

3 FE Model

3.1 FE Model description

The FE model, shown in the next figures, is made of:

- 185215 nodes
- 180784 two-dimensional elements (shell elements)
  - 178820 CQUAD4 elements
  - 1964 CTRIA3 elements
- 162 one-dimensional CBAR elements
- 364 Multi Point Constraints RBE2

Screw connections were simplified in the FE Model, and they were modeled through a beam element with suitable cross section, whose ends are connected to the shell by rigid elements.

The mesh of both fans, motors and impellers (components not subjected to verification in this work) was simplified, keeping the inertial properties unchanged.

The global size of the mesh is 10mm. In order to apply the *Hot Spot* method for the stress evaluation on the welds, the size of the mesh was reduced near the weld seams.

The global coordinate system used in this work (shown in the figures), is a rectangular Cartesian coordinate system where *x* axis is the longitudinal train direction, *y* axis is the transversal train direction and *z* axis is the vertical direction train. Measure units are millimeter [mm] for lengths, Newton [N] for forces and second [s] for time.

The calculated mass of the FE model is 564.8kg.

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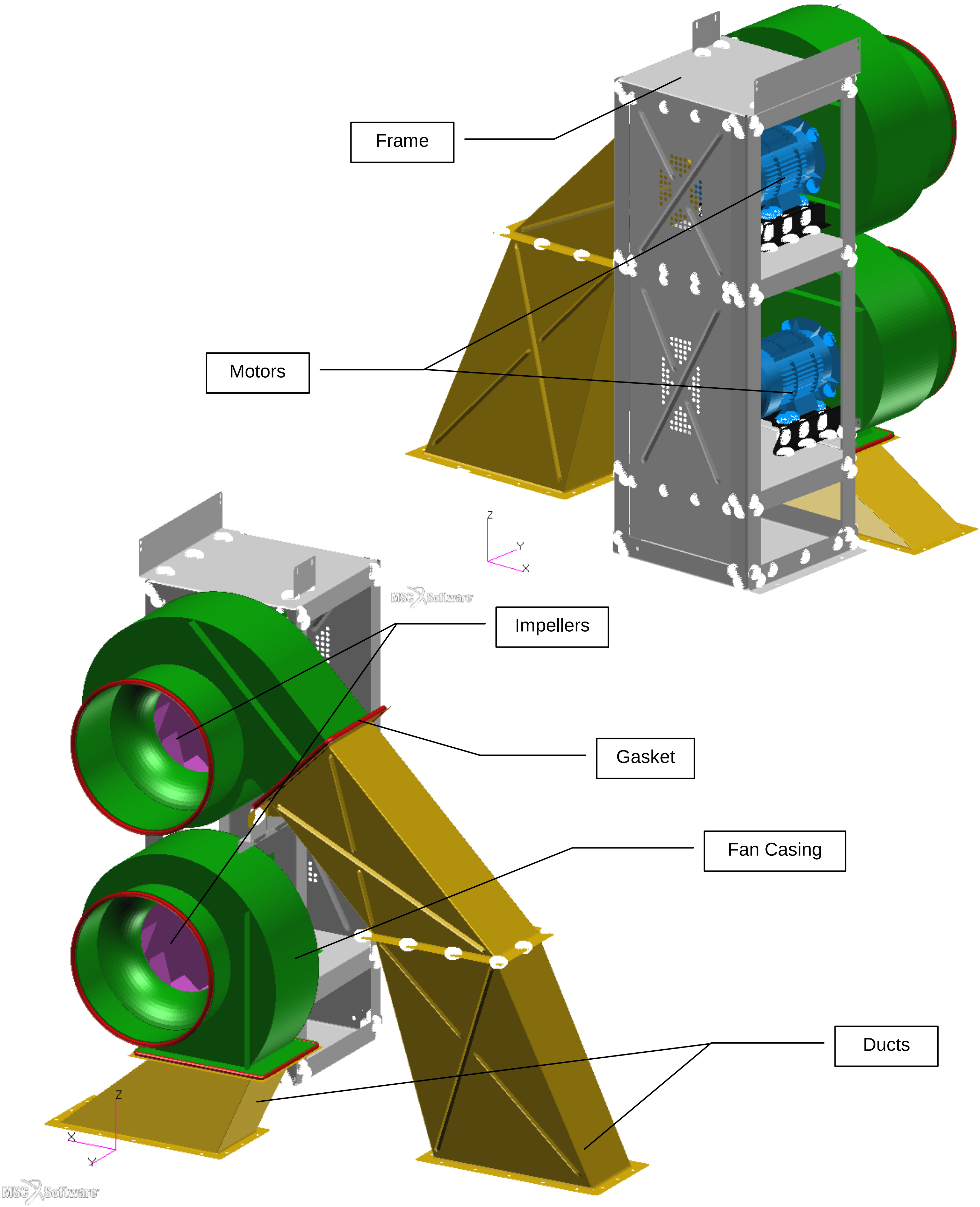
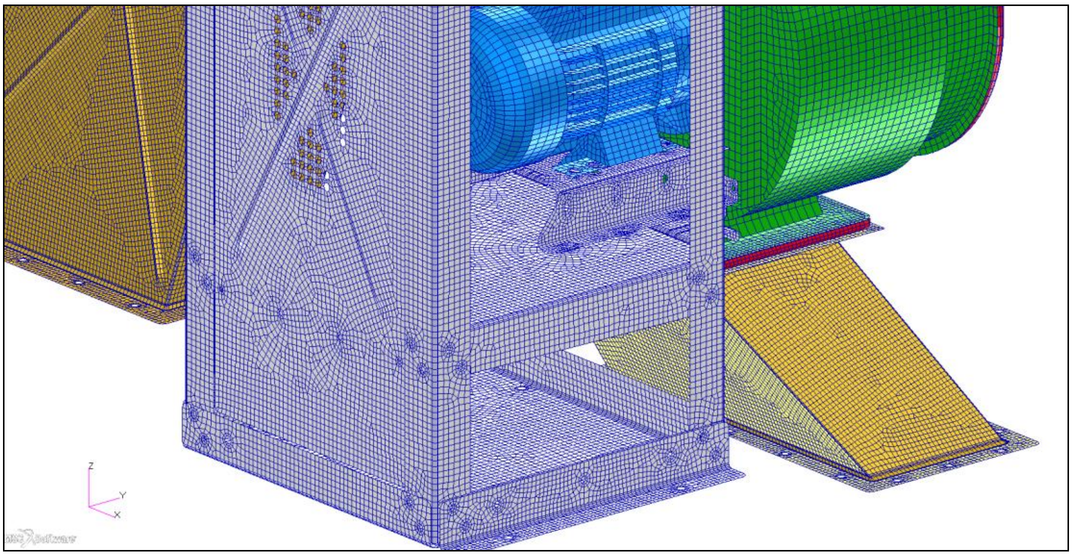
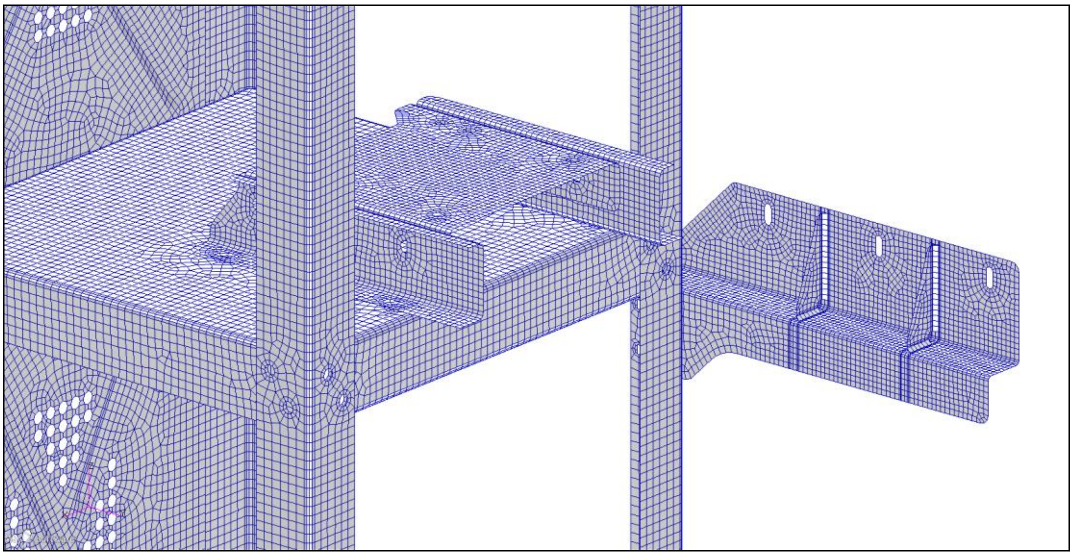


Figure 3.1 – TMB System FE Model (the white spiders are MPC constraints)





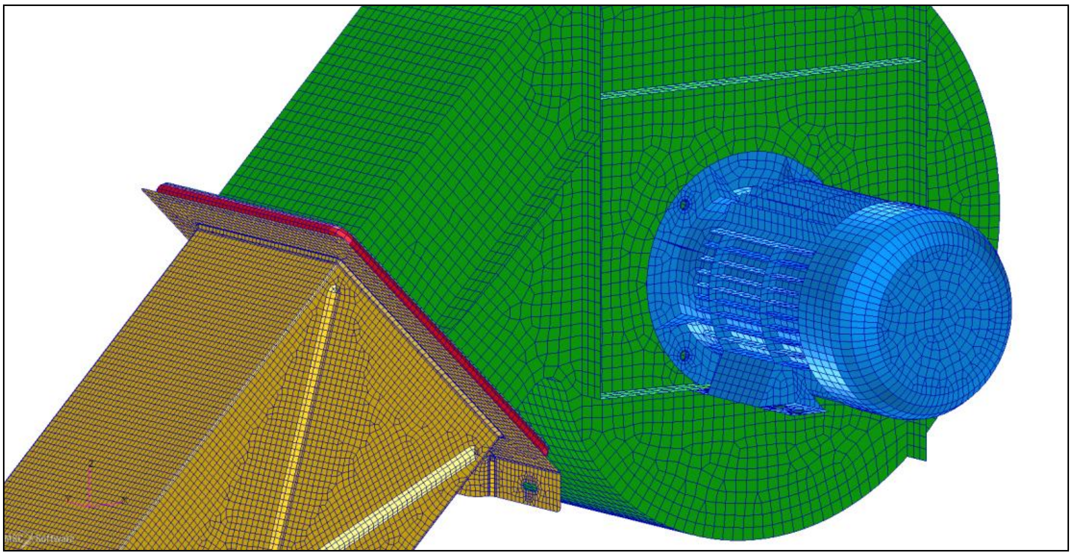


Figure 3.2 – Details of the TMB System FE Model

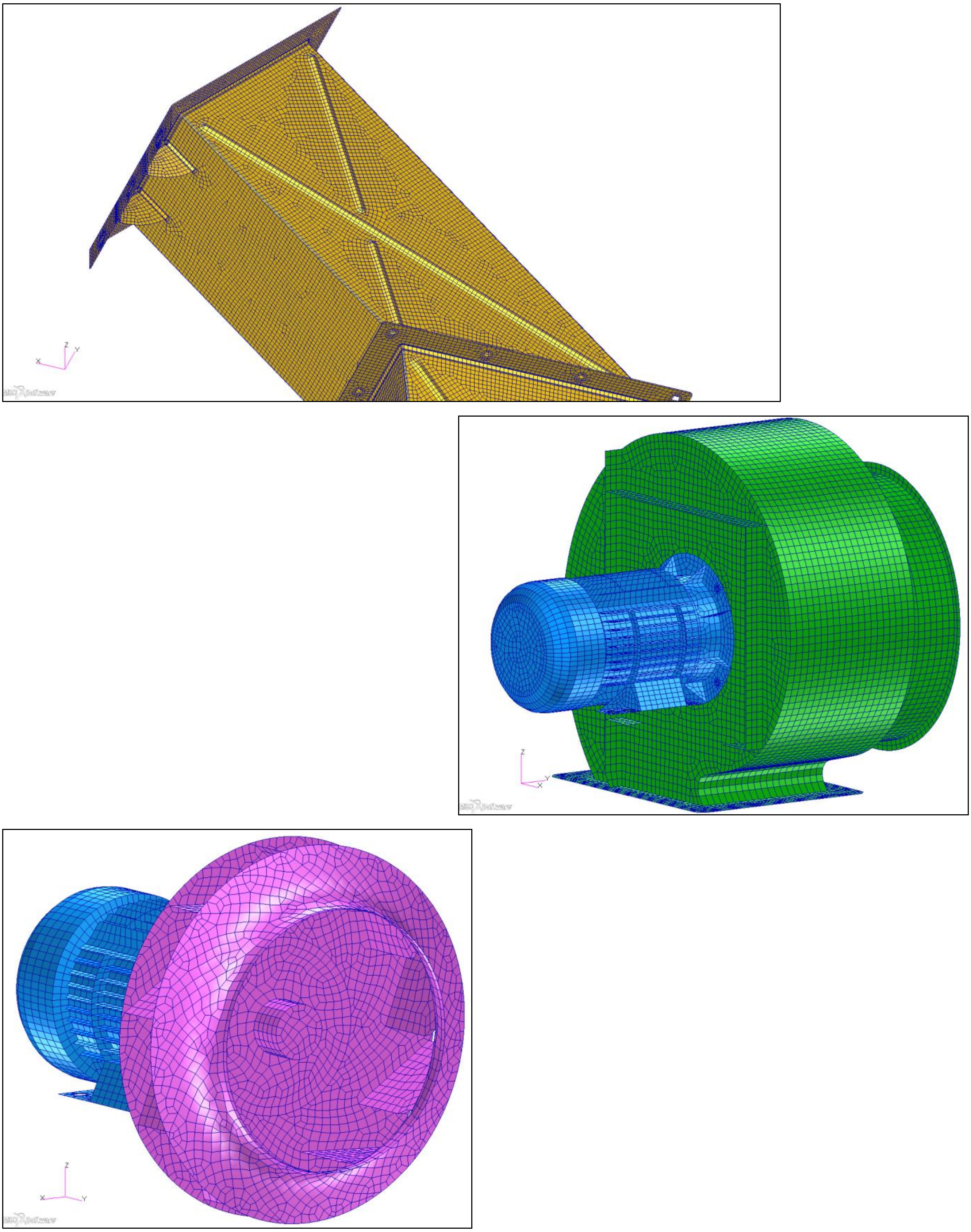


Figure 3.3 – Details of the Impeller, Motor and Duct FE Models

3.2 Model thickness

The shell thickness of the TMB System is shown in the next figure.

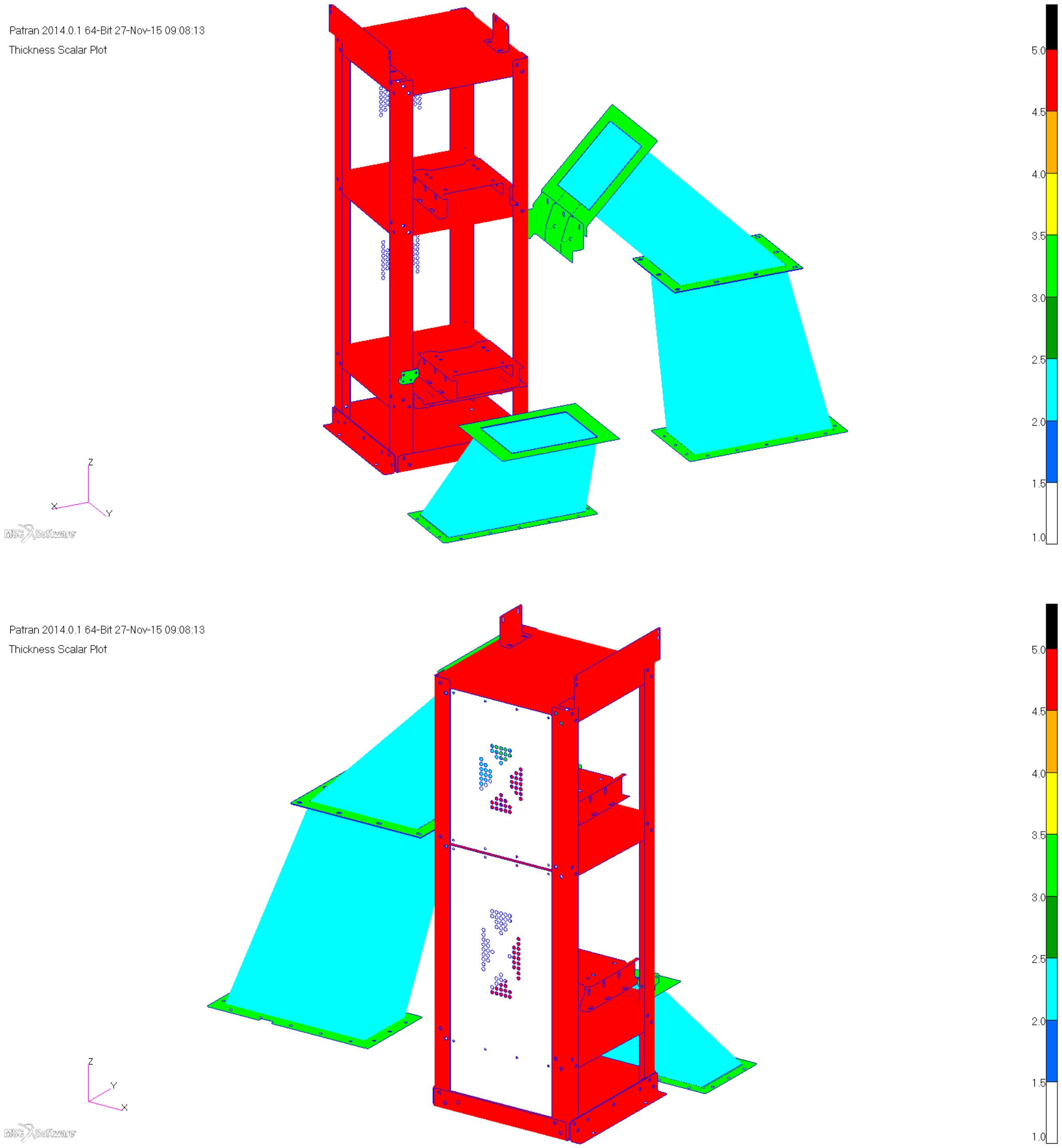


Figure 3.4 – TMB System shell thickness [mm]

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3.3 FE Model quality check

Next Table 3.1 shows the results of quality test carried out on the FE model (the elements that exceed the Nastran verification parameters are not in critical areas).

Type Check	Nastran Tolerance	Number of elements over tolerance	% on Total tria3/quad4 shell elements
Skew angle	< 30°	0	0%
Aspect Ratio	0.5	579	0.32%
Minimum Internal Angle	30°	24	0.01%
Maximum Internal Angle	150°	43	0.02%
Warp Factor	0.05	0	0%

Table 3.1 – FE Model check

3.4 Material properties

Materials and related mechanical properties used in the FE model are summarized in Table 3.2.

Component	Material	Yield Strength [MPa]	Ultimate Tensile Strength [MPa]	Young's Modulus [MPa]	Poisson's Ratio	Density [kg/mm^3]
Frame Ducts Impeller Fan frame	S355MC	355	510	206000	0.3	7.9e-6
Motor	Cast Iron	-	-	120000	0.3	7.3e-6
Gasket	EPDM	-	-	10	0.4	1.0e-6

Table 3.2 – Material properties

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4 Allowable stress values

4.1 Static loads

According to EN12663 and Customer Specification n.383601 Rev.0, the allowable stress values for the static loads (the same for welds and base material) are shown in the Table 4.1.

Static Loads Allowable Stress	***S355 MC***
Yield strength ($R_{p0.2}$/1.15)	308 MPa

Table 4.1 – Allowable stress for the static loads

4.2 Fatigue loads

The verification for the fatigue loads was carried out according to EN 1993-1-9 standard Annex B (*Fatigue resistance using the geometric - hot spot - stress method*).

The Fatigue Class (FAT, i.e. fatigue limit @ $2*10^6$ cycles) and the allowable stress values (stress range) @ 10^7 cycles for all details are summarized in the next table (a safety factor of 1.35 was considered).

Fatigue Loads Allowable Stress (stress range) @ 1e7 cycles – Safety factor ξ=1.35			
Material	**Detail**	**FAT**	**Stress Range**
S355 MC	Base material	160	76.0
	Fillet weld	90	42.8

Table 4.2 – Allowable stress for the fatigue loads

Next figures show the fatigue curves for all considered details.

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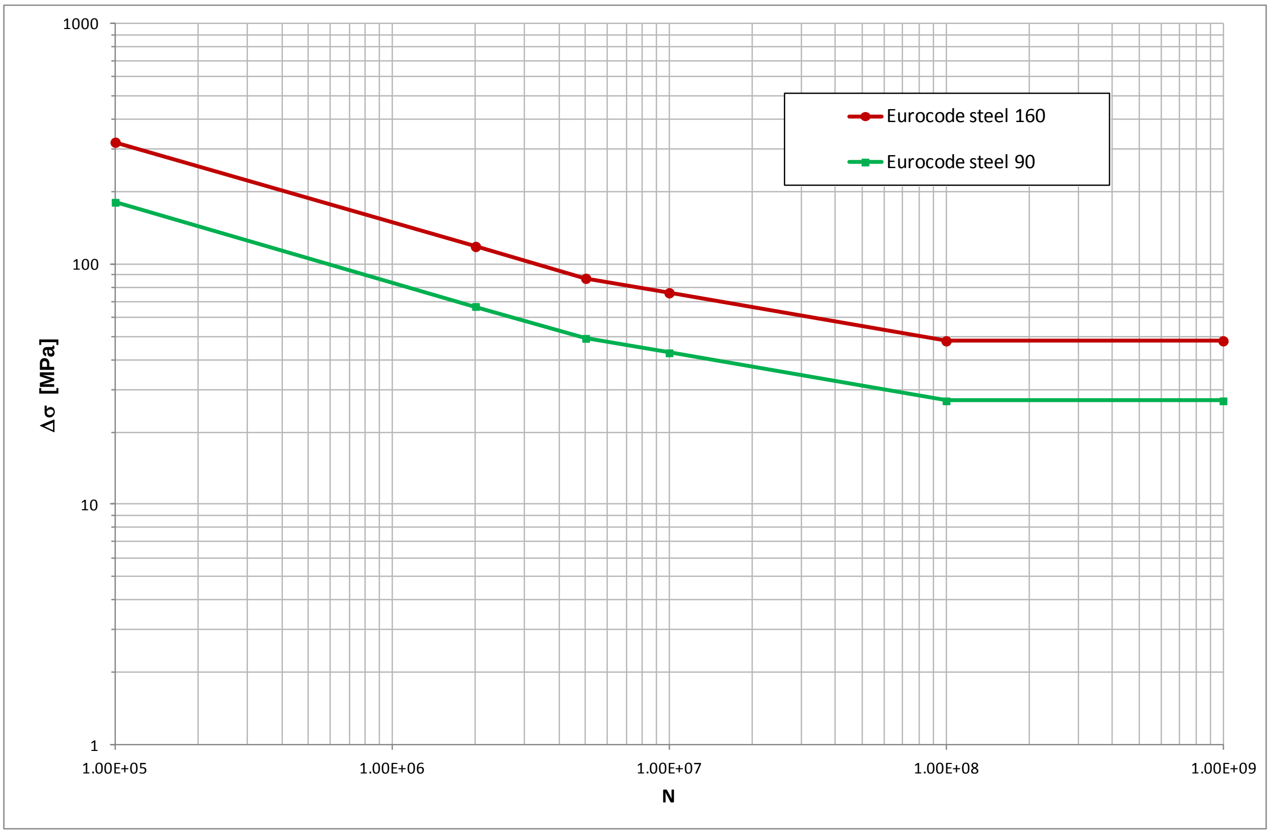
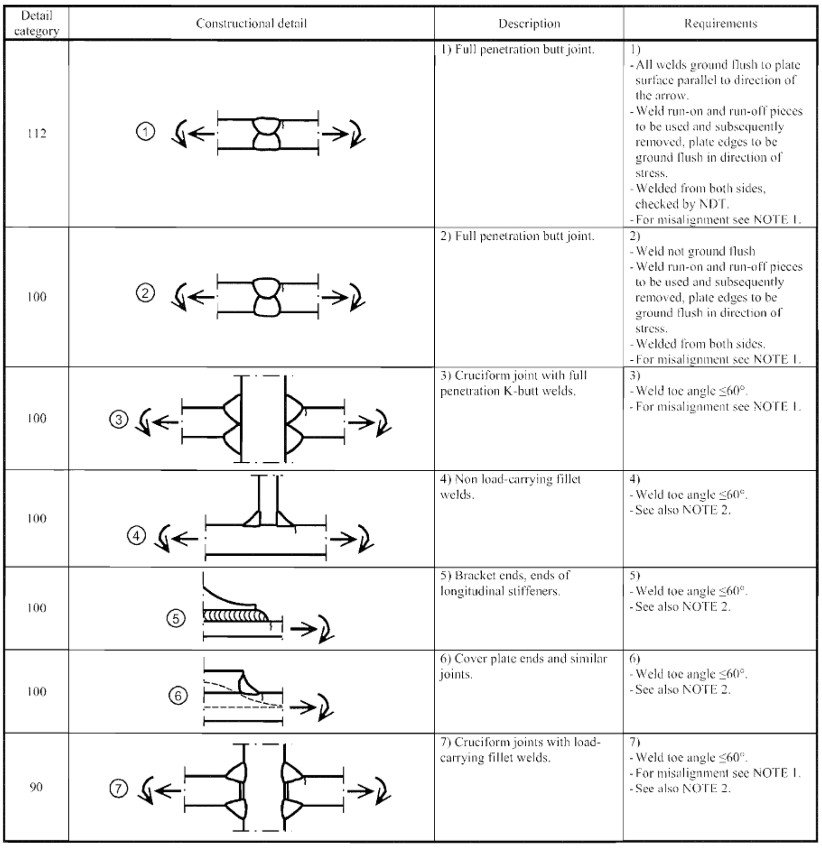


Figure 4.1 – Allowable fatigue strength for steel details (safety factor = 1.35)



Detail category	Constructional detail	Description	Requirements
112	①	1) Full penetration butt joint.	1) - All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides, checked by NDT. - For misalignment see NOTE 1.
100	②	2) Full penetration butt joint.	2) - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides. - For misalignment see NOTE 1.
100	③	3) Cruciform joint with full penetration K-butt welds.	3) - Weld toe angle ≤60°. - For misalignment see NOTE 1.
100	④	4) Non load-carrying fillet welds.	4) - Weld toe angle ≤60°. - See also NOTE 2.
100	⑤	5) Bracket ends, ends of longitudinal stiffeners.	5) - Weld toe angle ≤60°. - See also NOTE 2.
100	⑥	6) Cover plate ends and similar joints.	6) - Weld toe angle ≤60°. - See also NOTE 2.
90	⑦	7) Cruciform joints with load-carrying fillet welds.	7) - Weld toe angle ≤60°. - For misalignment see NOTE 1. - See also NOTE 2.

Figure 4.2 – Extract of Fatigue Class according to EN 1993-1-9 standard, Annex B

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5 Load Cases

5.1 Static loads

The following static load conditions were considered:

Load Cases	Load Condition	***Load (g = 9.806m/s²)***		
		x	*y*	*z*
Longitudinal acceleration	S01	+5g	-	-1g
	S02	-5g	-	-1g
Lateral acceleration	S03	-	+1g	-1g
	S04	-	-1g	-1g
Vertical acceleration	S05	-	-	-3g
	S06	-	-	+1g

Table 5.1 – Static load conditions

5.2 Fatigue loads

The following fatigue load conditions, and related combinations, were considered:

Load Cases	Load Condition	***Load (g = 9.806m/s²)***		
		x	*y*	*z*
Longitudinal acceleration	F01	-0.15g	-	-1g
	F02	+0.15g	-	-1g
Lateral acceleration	F03	-	-0.15g	-1g
	F04	-	+0.15g	-1g
Vertical acceleration	F05	-	-	-1.15g
	F06	-	-	-0.85g

Table 5.2 – Fatigue load conditions

5.3 Modal analysis

The modal analysis was carried out, and the natural frequencies of the structure were calculated.

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6 Boundary conditions

The FE Model was constrained at ground in correspondence of the holes of the plate's frame, and in correspondence of the holes of the low duct, as show in the next figures. In addition, the round gaskets of the fan frames were constrained at ground. These constraints were used in both structural and modal analyses.

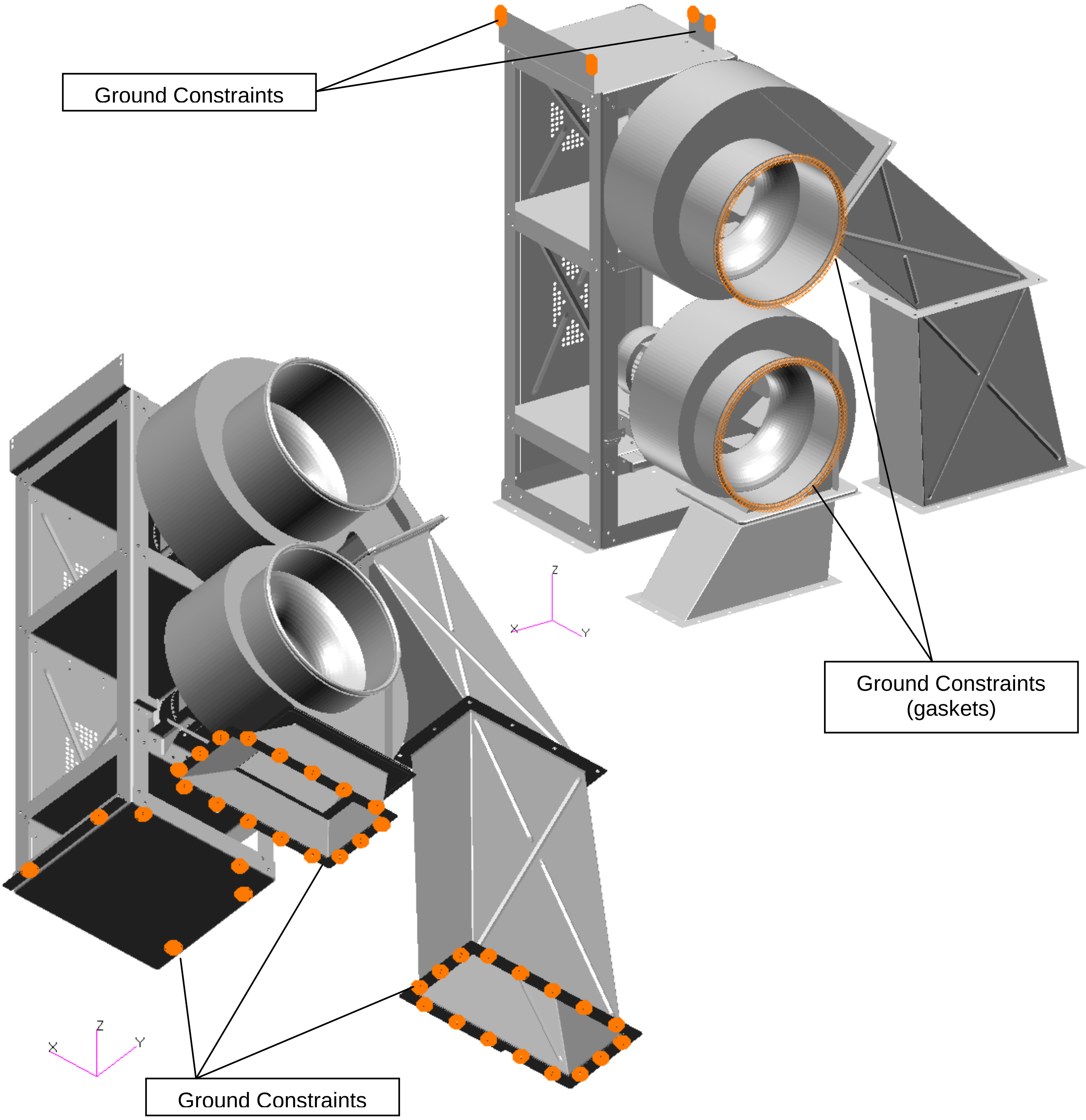

Figure 6.1 – TMB System boundary conditions

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7 Static load conditions results

7.1 Load Condition S01

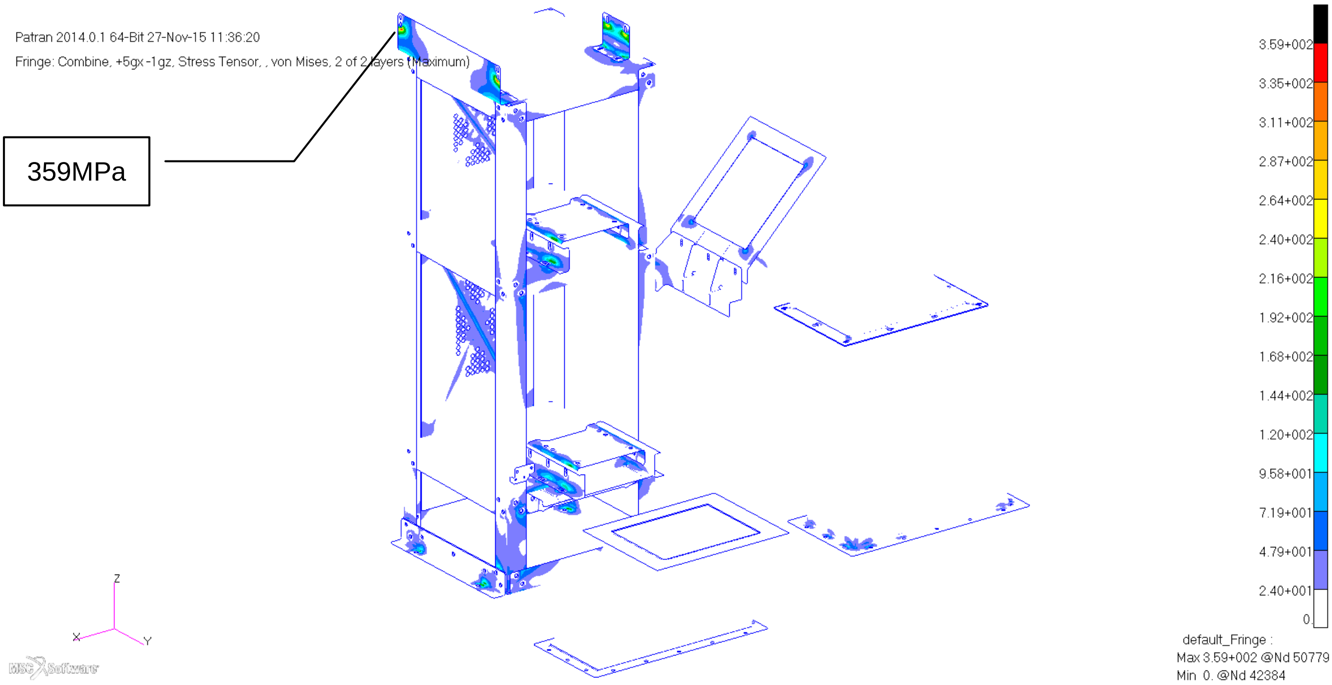

Figure 7.1 – Von Mises stress [MPa] for Load Condition S01

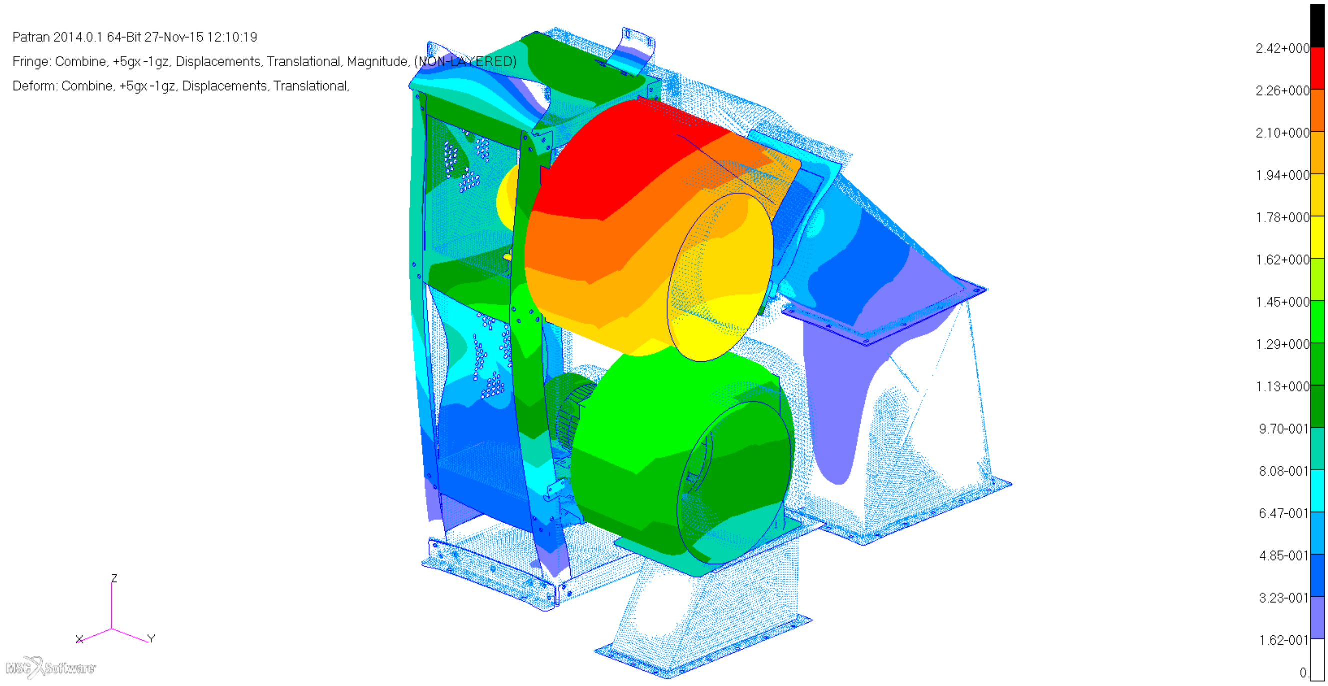

Figure 7.2 – Displacement (magnitude) [mm] for Load Condition S01 (magnification x100)

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7.2 Load Condition S02

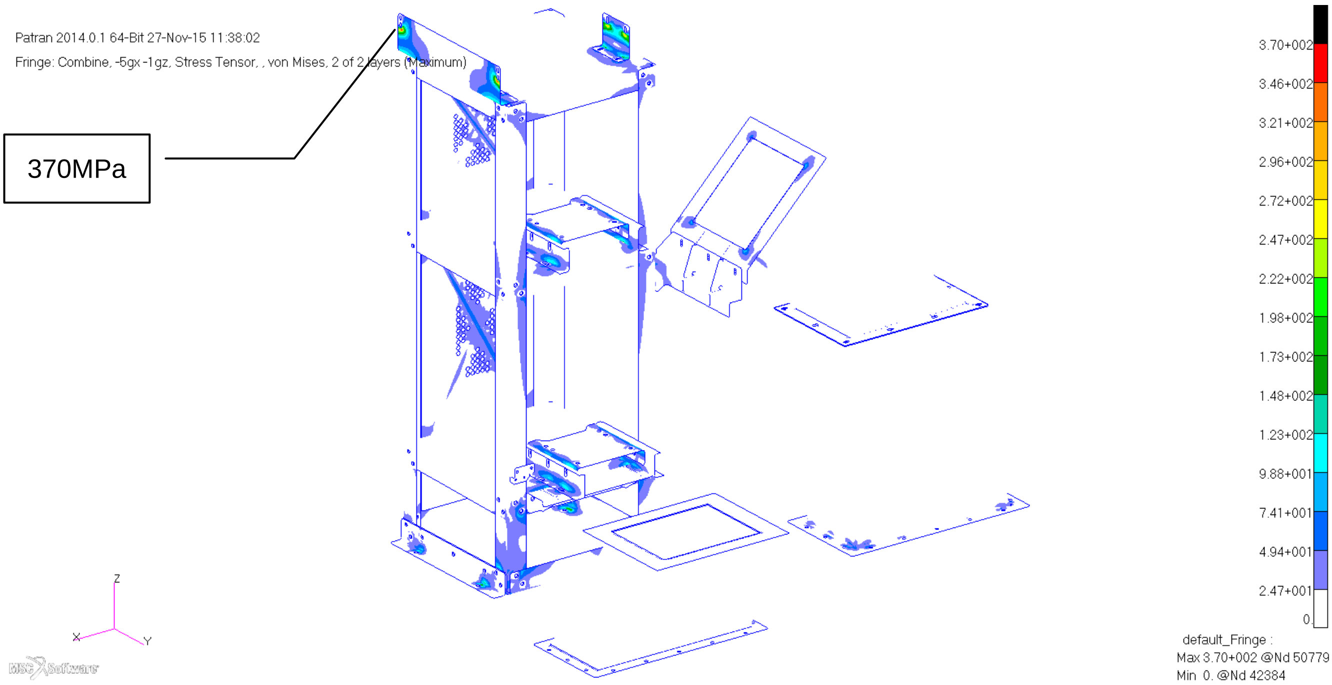

Figure 7.3 – Von Mises stress [MPa] for Load Condition S02

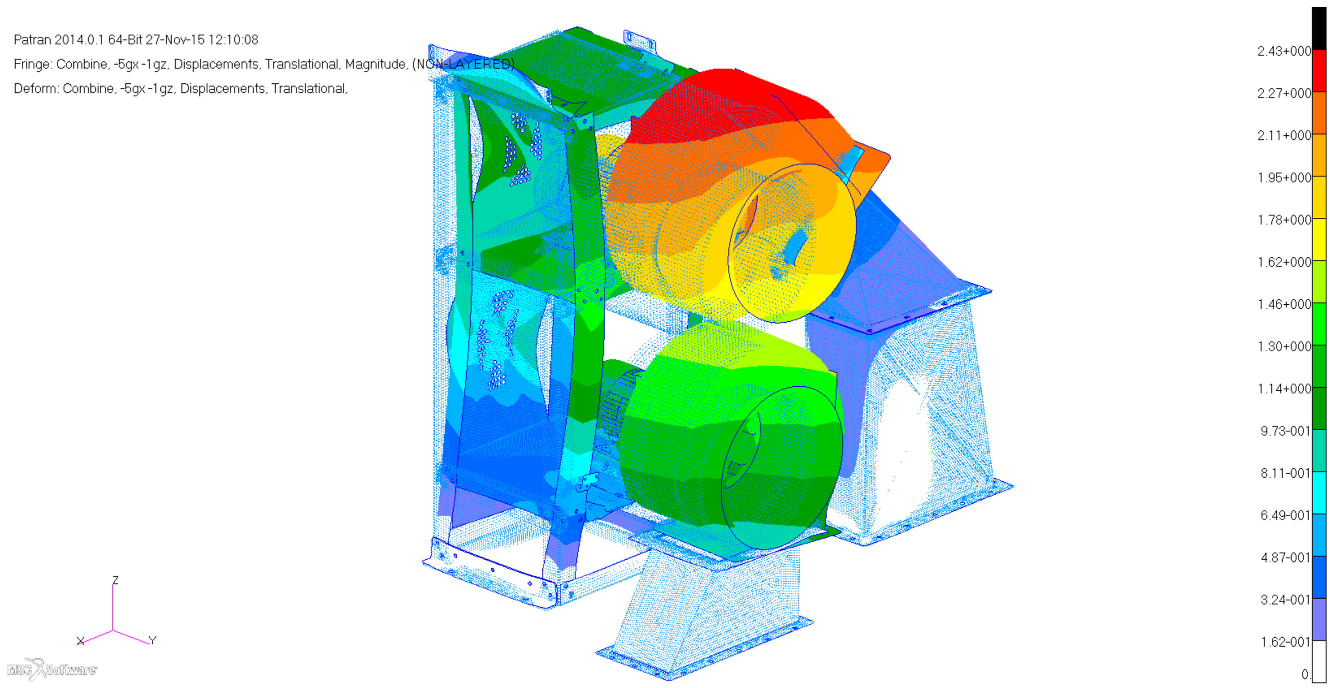

Figure 7.4 – Displacement (magnitude) [mm] for Load Condition S02 (magnification x100)

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7.3 Load Condition S03

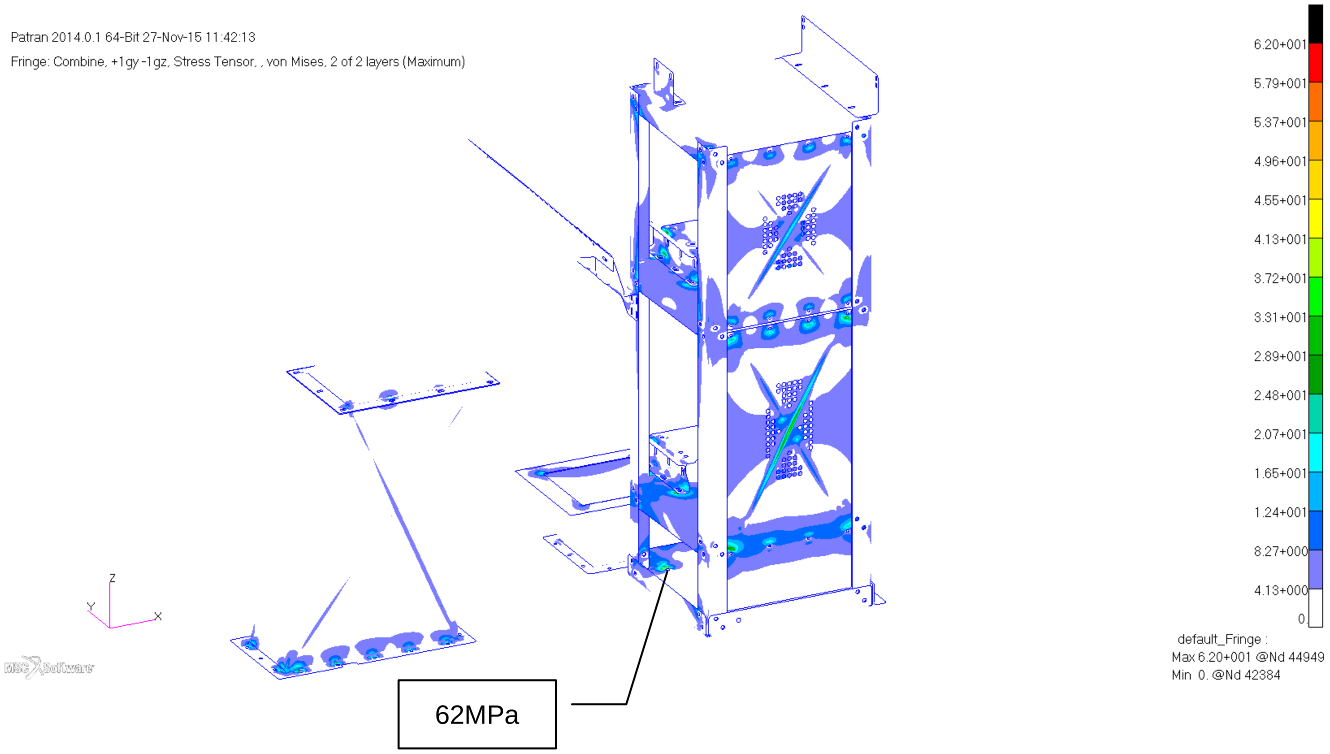

Figure 7.5 – Von Mises stress [MPa] for Load Condition S03

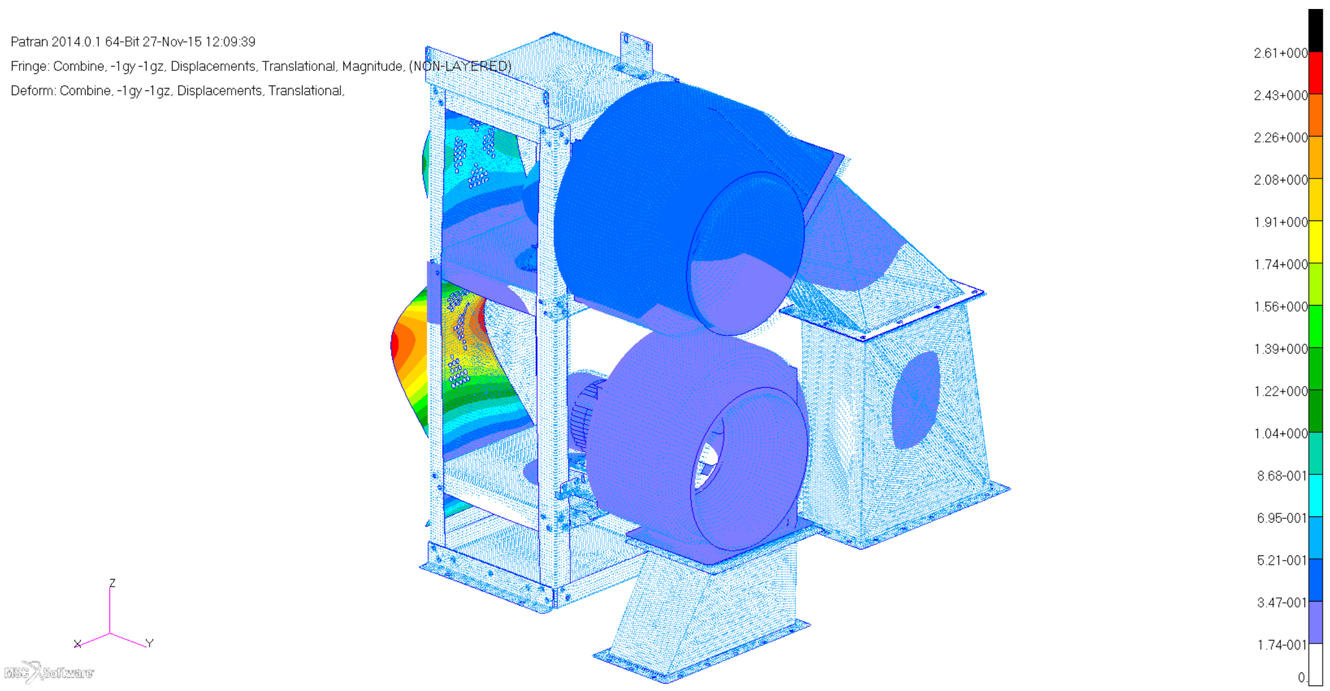

Figure 7.6 – Displacement (magnitude) [mm] for Load Condition S03 (magnification x100)

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7.4 Load Condition S04

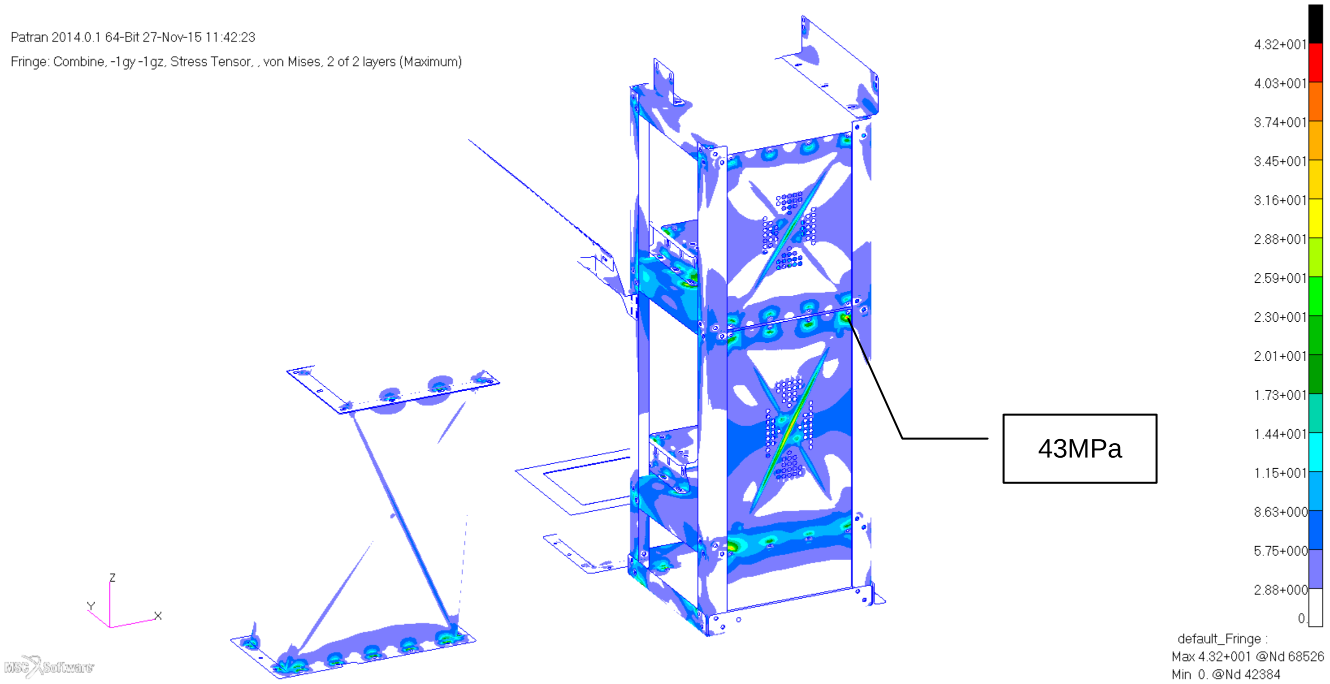

Figure 7.7 – Von Mises stress [MPa] for Load Condition S04

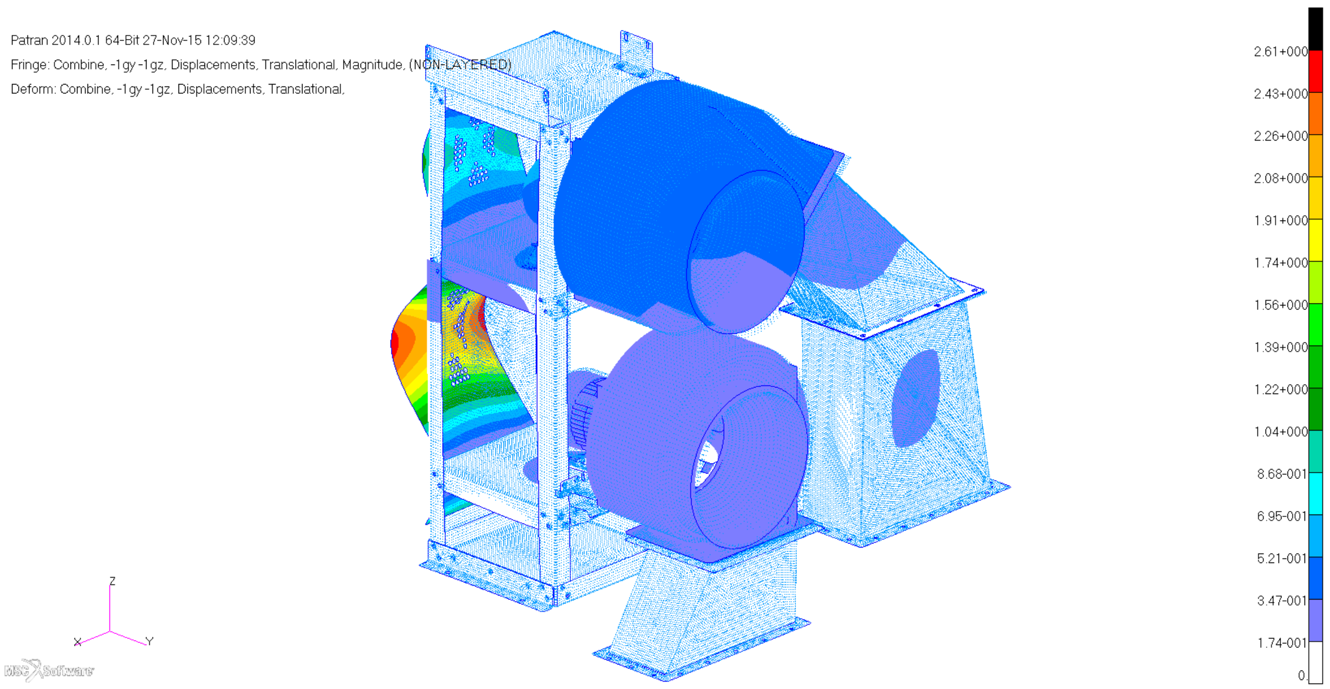

Figure 7.8 – Displacement (magnitude) [mm] for Load Condition S04 (magnification x100)

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7.5 Load Condition S05

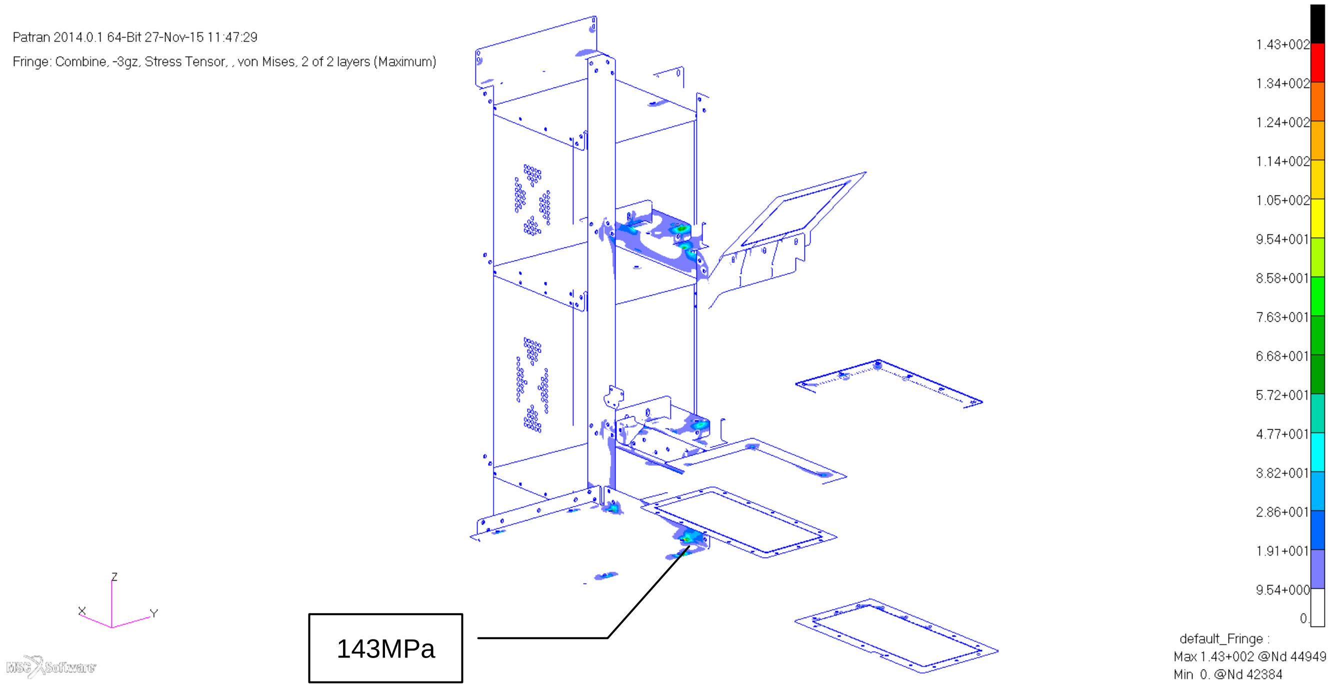

Figure 7.9 – Von Mises stress [MPa] for Load Condition S05

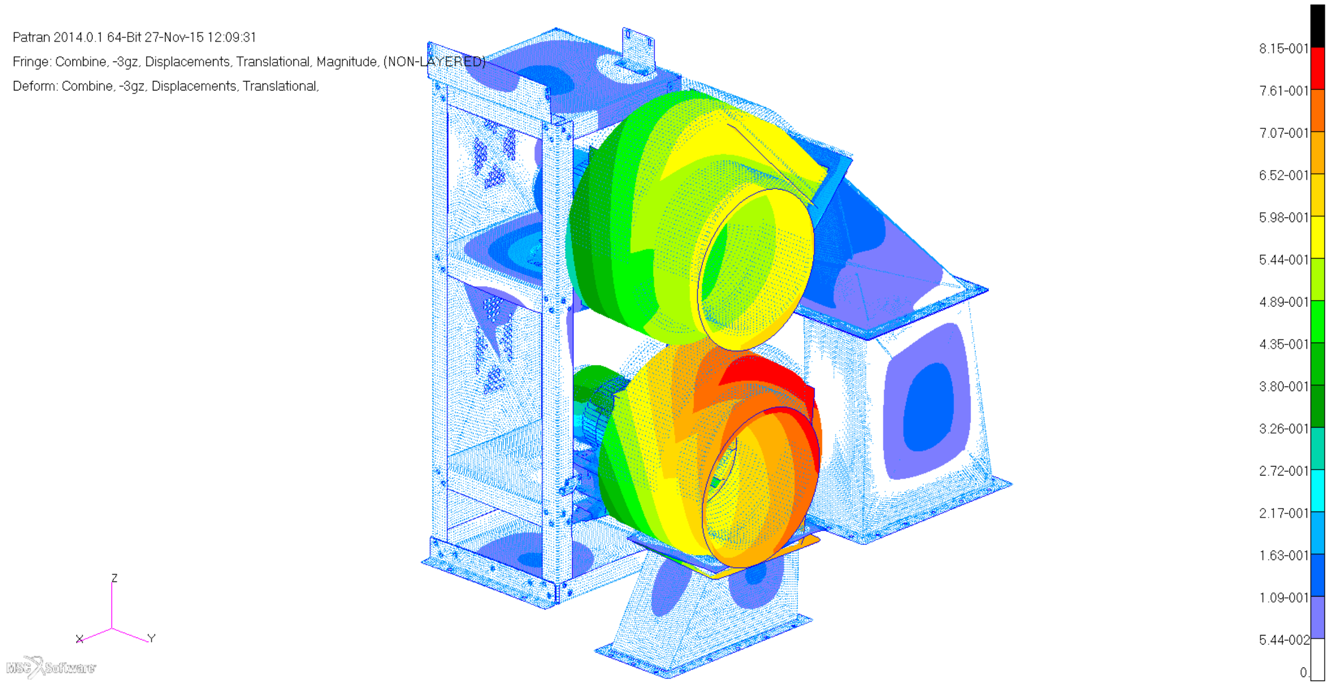

Figure 7.10 – Displacement (magnitude) [mm] for Load Condition S05 (magnification x100)

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7.6 Load Condition S06

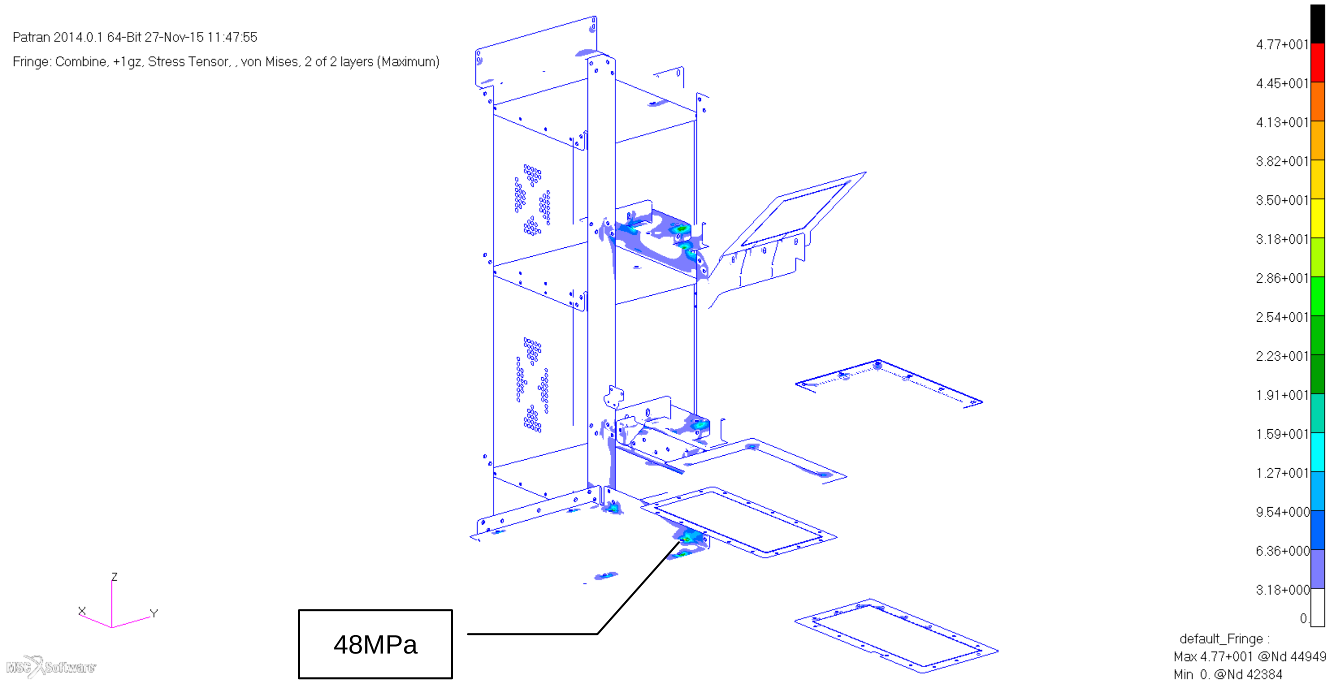

Figure 7.11 – Von Mises stress [MPa] for Load Condition S06

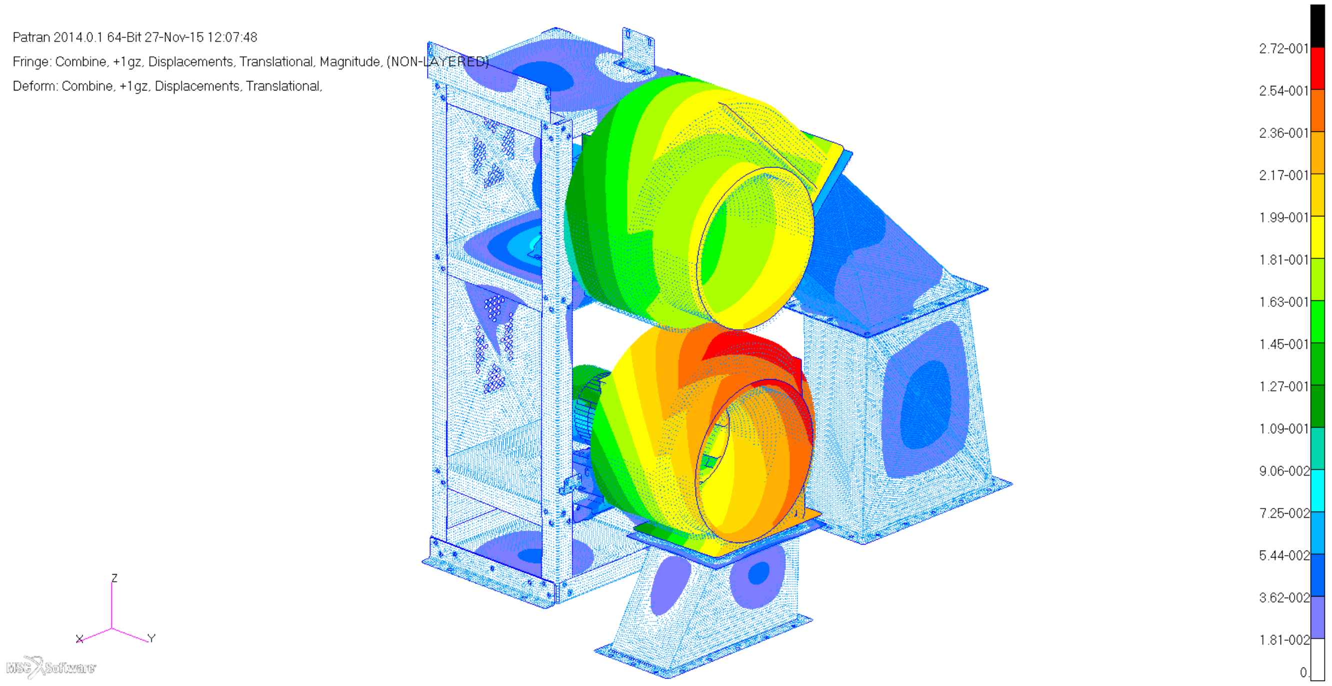

Figure 7.12 – Displacement (magnitude) [mm] for Load Condition S06 (magnification x100)

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7.7 Static Loads Assessment

The calculated Von Mises stress is lower than the allowable one ($R_{p0.2}$/1.15=308MPa) for load conditions S03-S06.

For load condition S01 and S02, there are very local areas (near rigid links) where the calculated stress is higher than the allowable one (this condition is allowed by the Customer Specification). As regards these areas, one can observe that a local plastic deformation could be expected, but not high enough to lead to a significant permanent deformation of the structure.

For load conditions S01 and S02, elastic-plastic analyses where performed (see next figures), and the maximum calculated plastic strains were found to be very low (0.03%) compared with the elongation to fracture for this material (22%).

Static Loads Verification		
Load condition	*Maximum Calculated Von Mises stress [MPa]*	*Allowable stress [MPa]*
S01	*359*	308 ($R_{p0.2}$/1.15)
S02	*370*	
S03	62	
S04	43	
S05	143	
S06	48	
Load condition	*Maximum Calculated Plastic Strain*	*Elongation to fracture*
S01	0.03%	22%
S02	0.04%	

Table 7.1 – Static Load assessment summary

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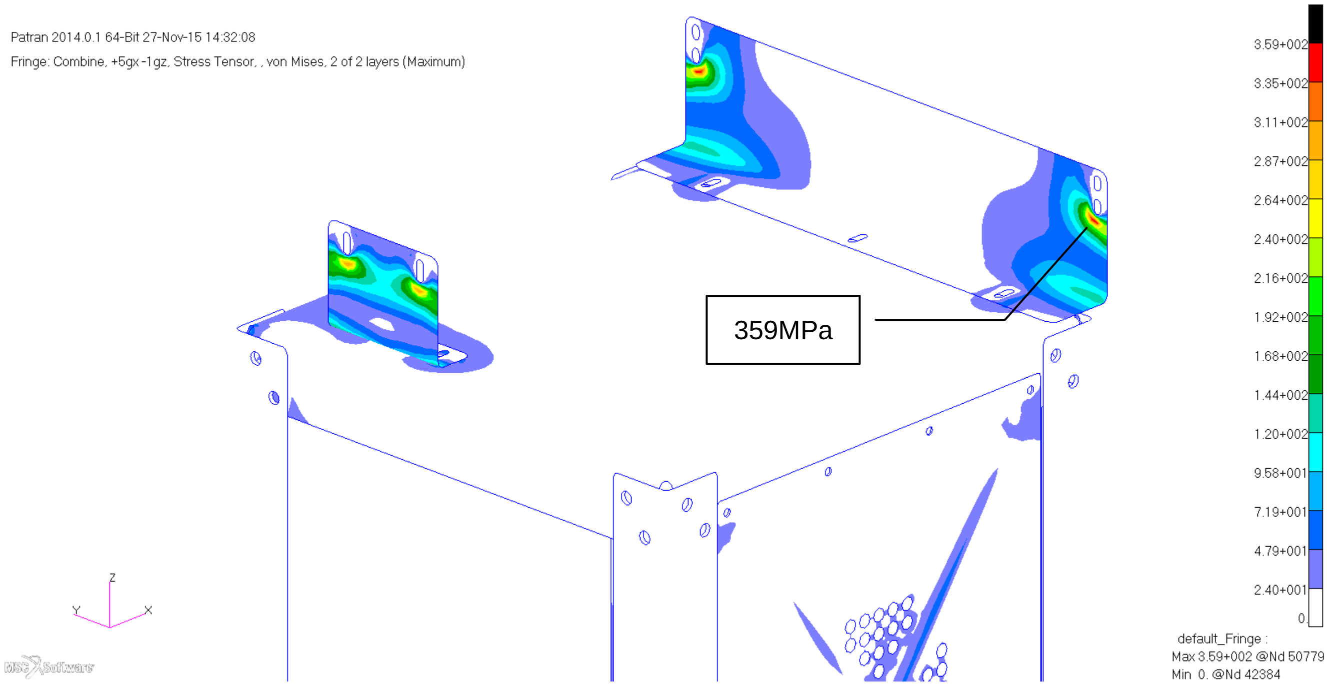

Figure 7.13 – Von Mises stress [MPa] for Load Condition S01 – Peak areas near the rigid link

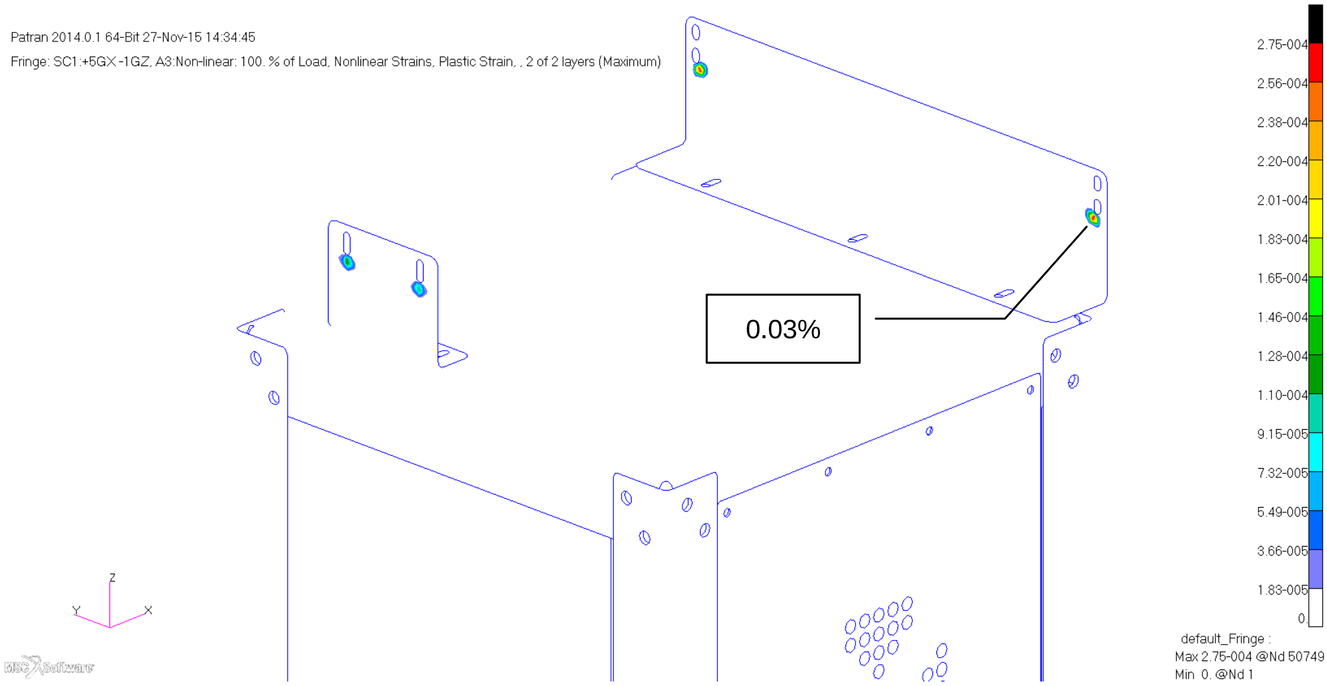

Figure 7.14 – Plastic strain for Load Condition S01

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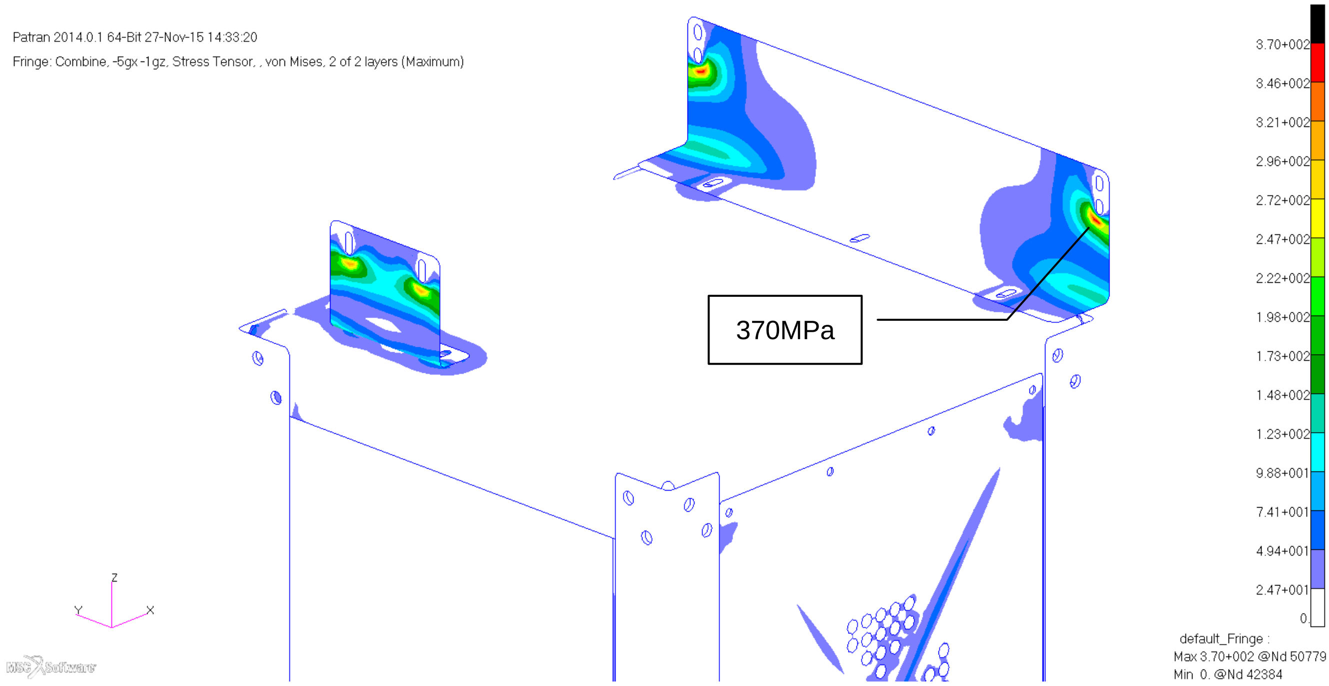

Figure 7.15 – Von Mises stress [MPa] for Load Condition S02 – Peak areas near the rigid link

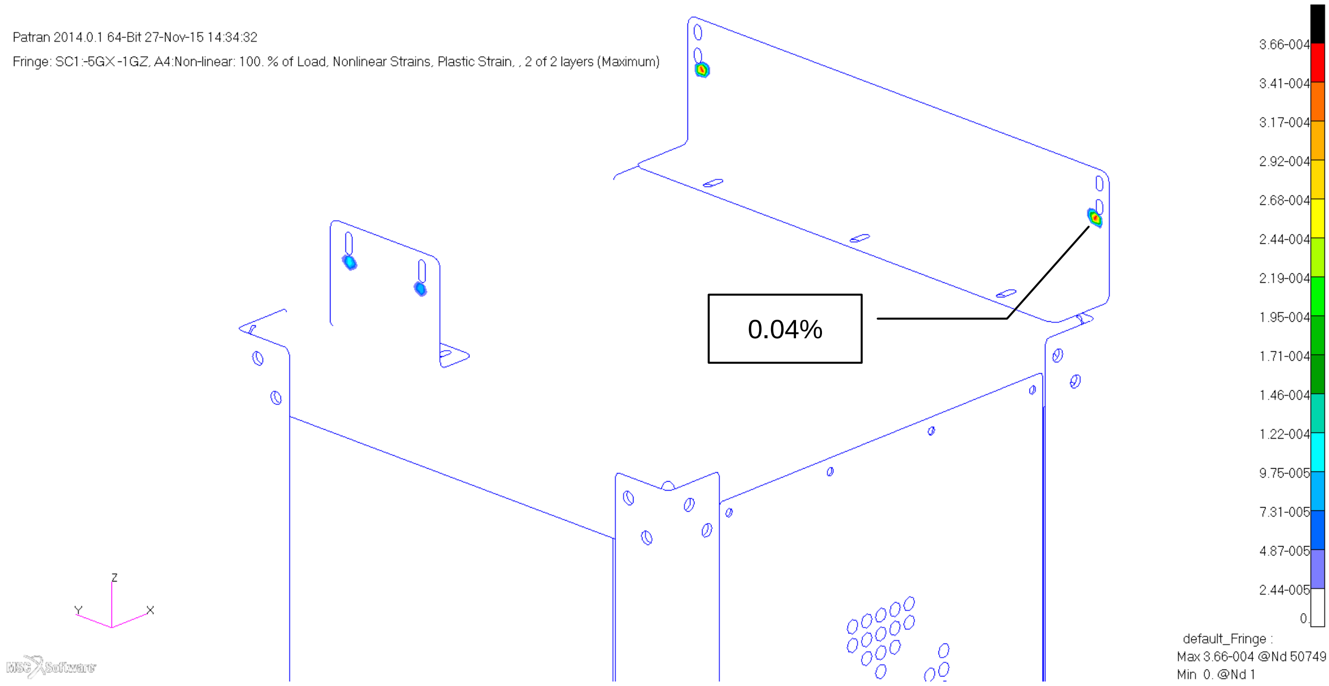

Figure 7.16 – Plastic strain for Load Condition S02

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8 Fatigue load conditions results

The results of the fatigue load assessment are summarized in the next table (only the most critical position for each load case is reported), and the significant areas are shown and indicated in the next figures.

For what concerns the welds, the most critical position is always the fillet weld between the fan casing and brackets (FAT of this type of weld is 90, so the butt joints with FAT 100 are verified as well).

One can see that the calculated stress range[1] is always lower than the allowable one.

Fatigue Loads Verification					
Position	Load Cases	Maximum Principal stress [MPa]	Minimum Principal stress [MPa]	Maximum calculated stress range [MPa]	Allowable stress range @ 10^7 cycles [MPa]
Base Material (FAT 160)	Longitudinal acceleration	33.9	-28.2	62.1	76.0
	Lateral acceleration	37.8	-25.5	63.3	
	Vertical acceleration	41.6	30.8	10.8	
Load Carrying Fillet weld (FAT 90)	Longitudinal acceleration	15.5	0.0	15.5	42.8
	Lateral acceleration	15.0	0.0	15.0	
	Vertical acceleration	16.5	12.1	4.4	

Table 8.1 – Fatigue Load assessment summary

According to IIW Fatigue Recommendations IIW-1823-07 Dec. 2008 (*Recommendation for fatigue design of welded joints and components*), the stress on the weld toe was determined by the Hot Spot Method, i.e. with a linear extrapolation of the calculated stresses on relevant points (0.4t and 1.0t), as shown in the next figures.

[1] For any point of verification, the stress range is the sum (with sign) of the Maximum and Minimum Principal stresses calculated in that point.

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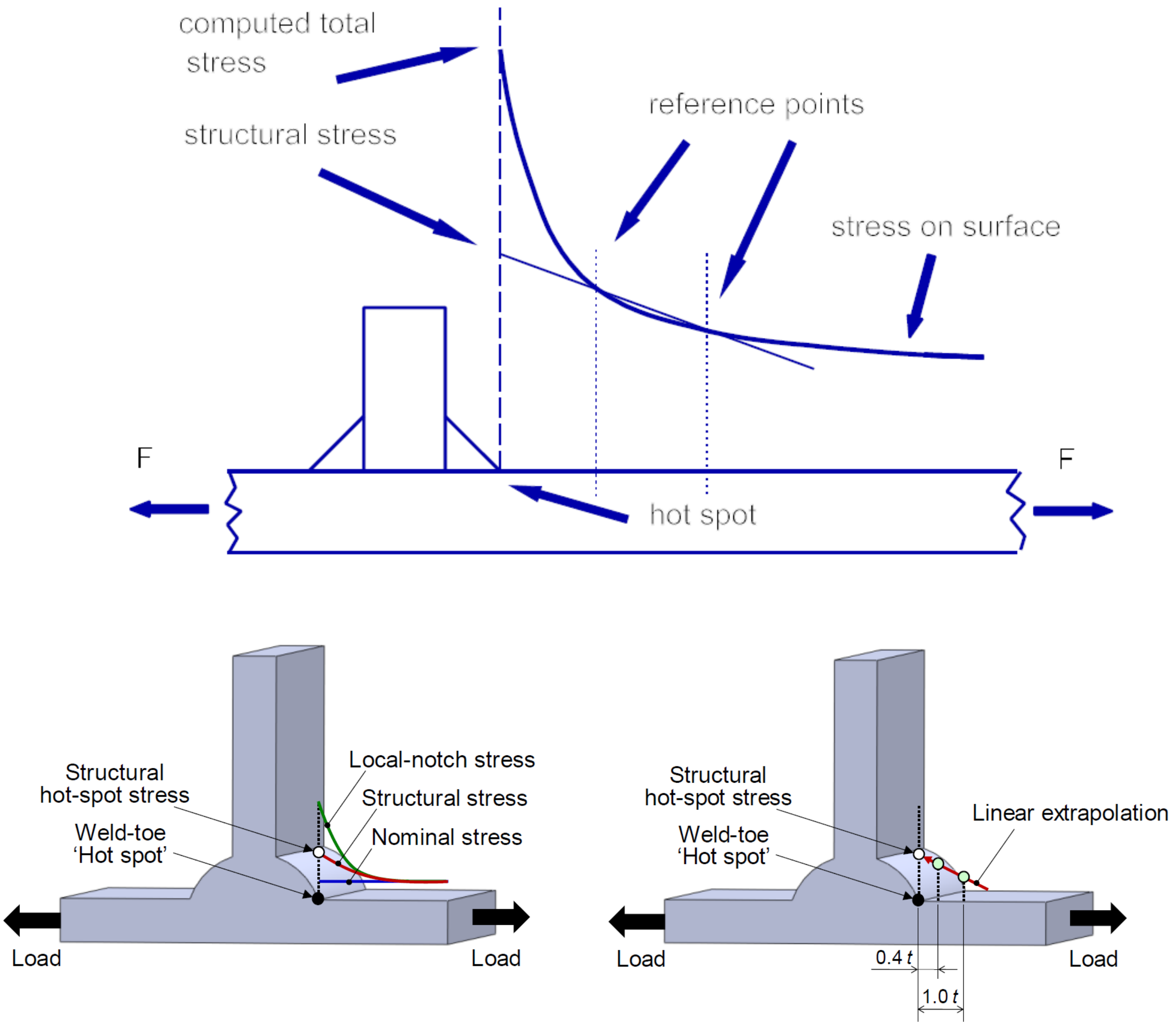

Figure 8.1 – Hot Spot Method[2] (extrapolation of the structural stress at the weld toe)

[2] Figures from *IIW Fatigue Recommendations IIW-1823-07 Dec. 2008* and paper *Can we optimally design light-weight welded structures with sufficient fatigue resistance?*, Norio Takeda and Tomohiro Naruse, 10th World Congress on Structural and Multidisciplinary Optimization.

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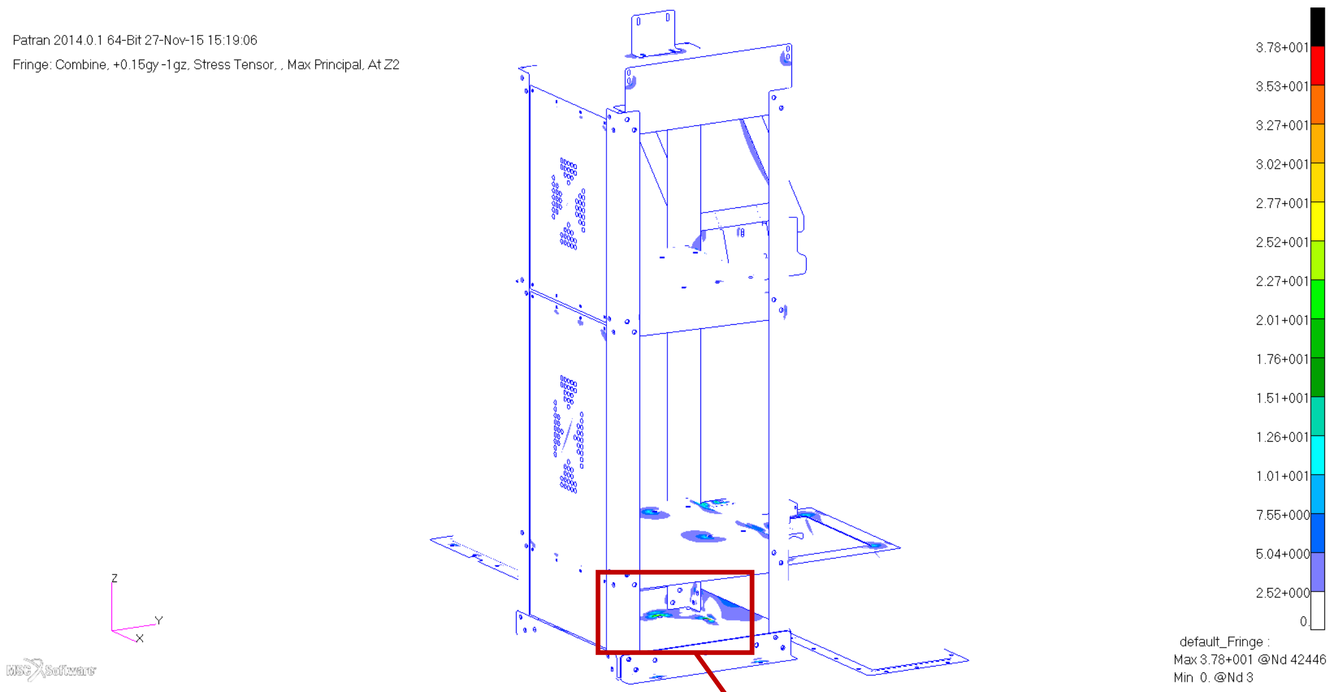

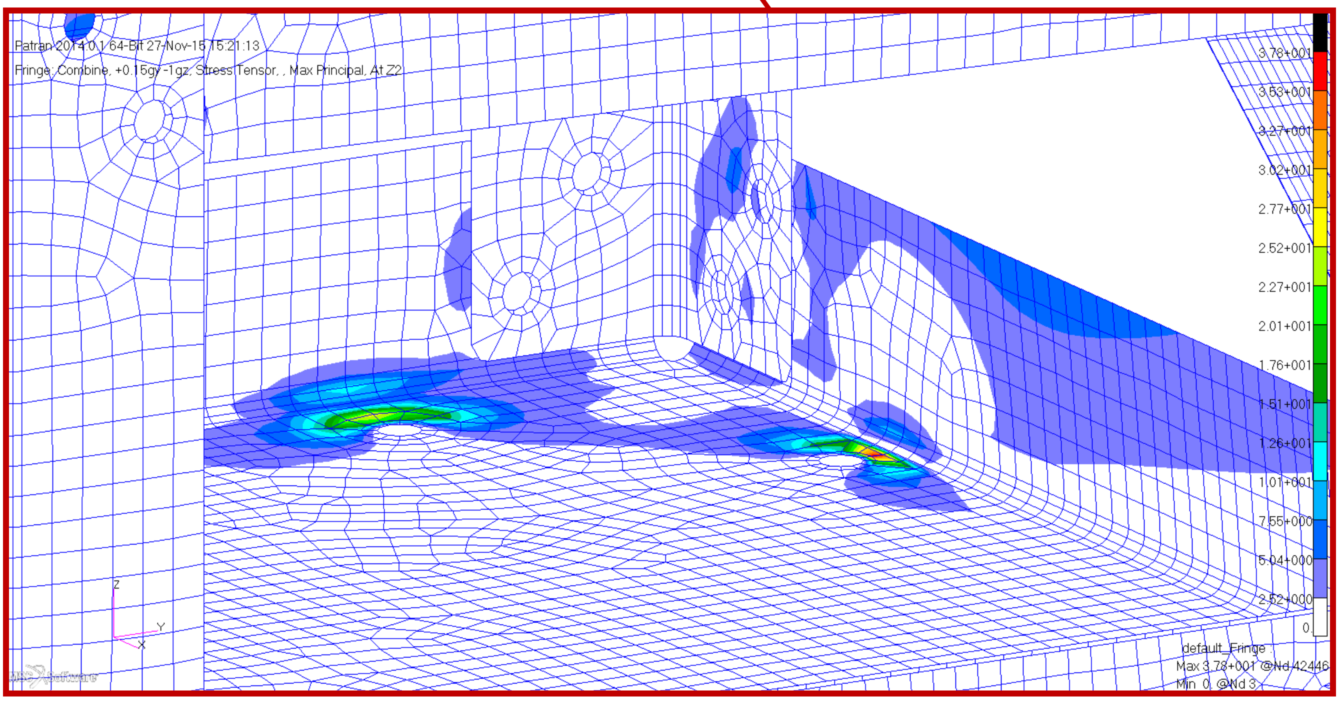

Figure 8.2 – Maximum Principal calculated stress [MPa] for the Lateral acceleration (load combination with maximum calculated stress range) on the S355MC base material

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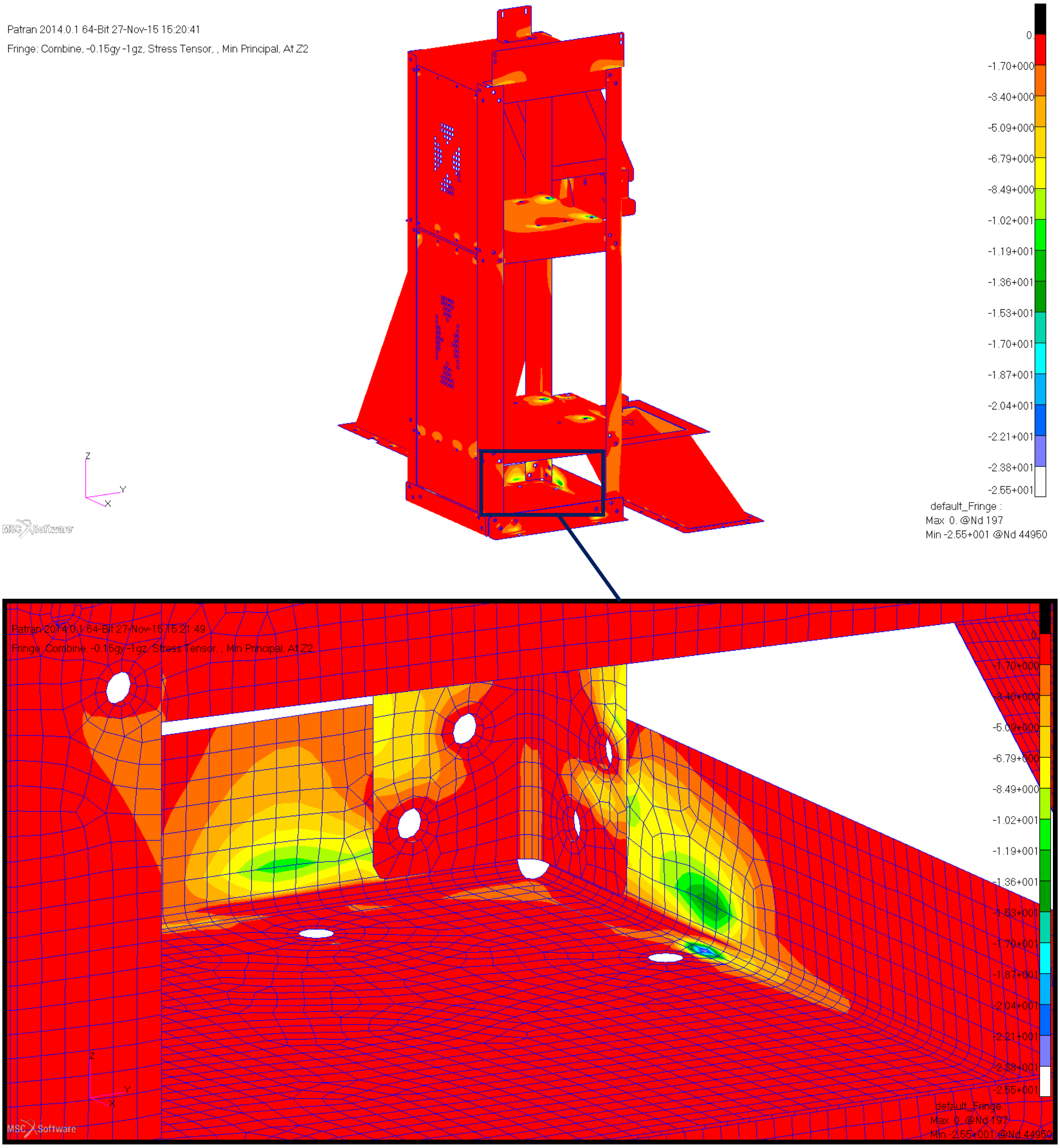

Figure 8.3 – Minimum Principal calculated stress [MPa] for the Lateral acceleration (load combination with maximum calculated stress range) on the S355MC base material

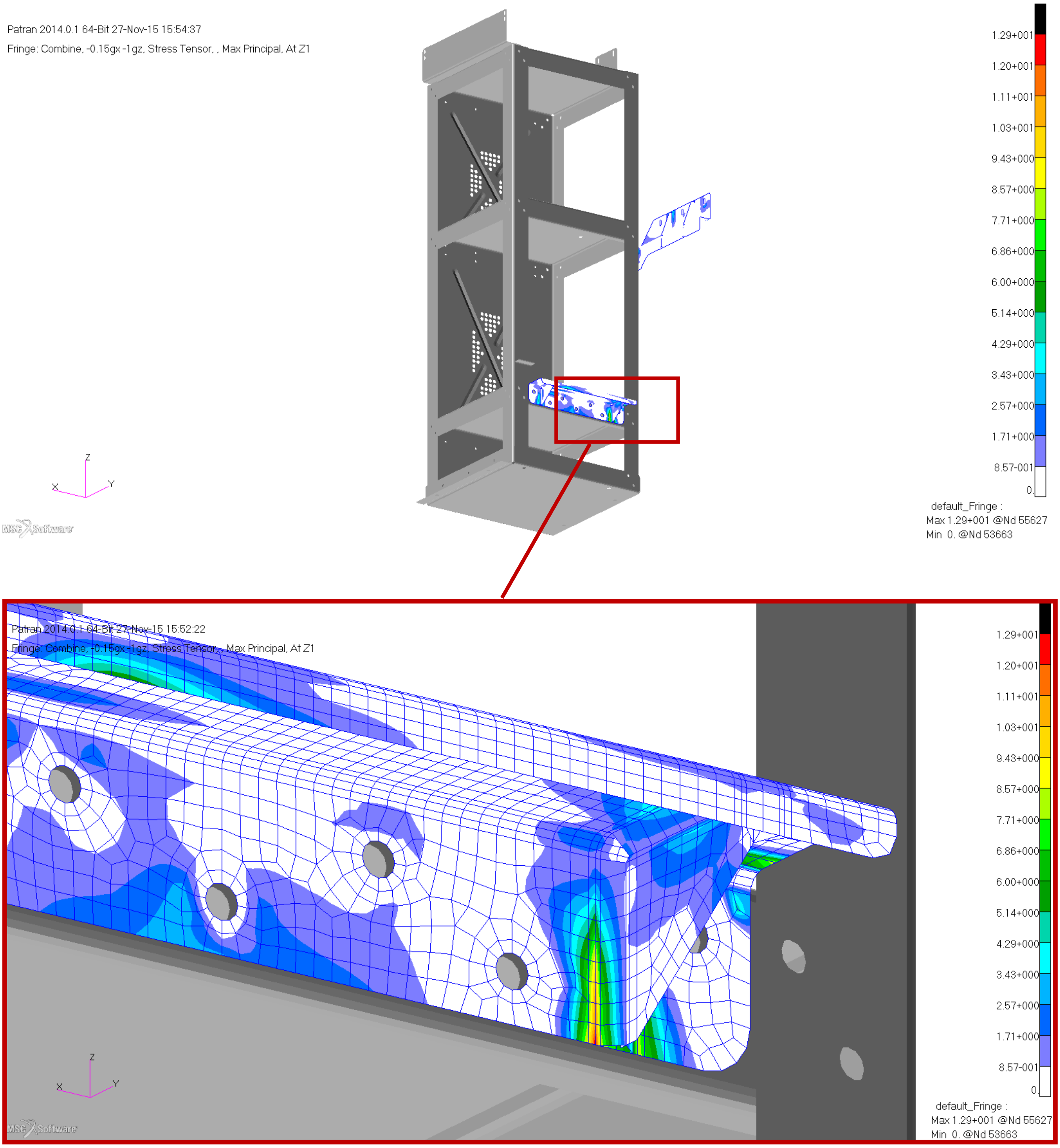

Figure 8.4 – Maximum Principal calculated stress [MPa] for the Longitudinal acceleration (load combination with maximum calculated stress range) on the S355MC fillet weld

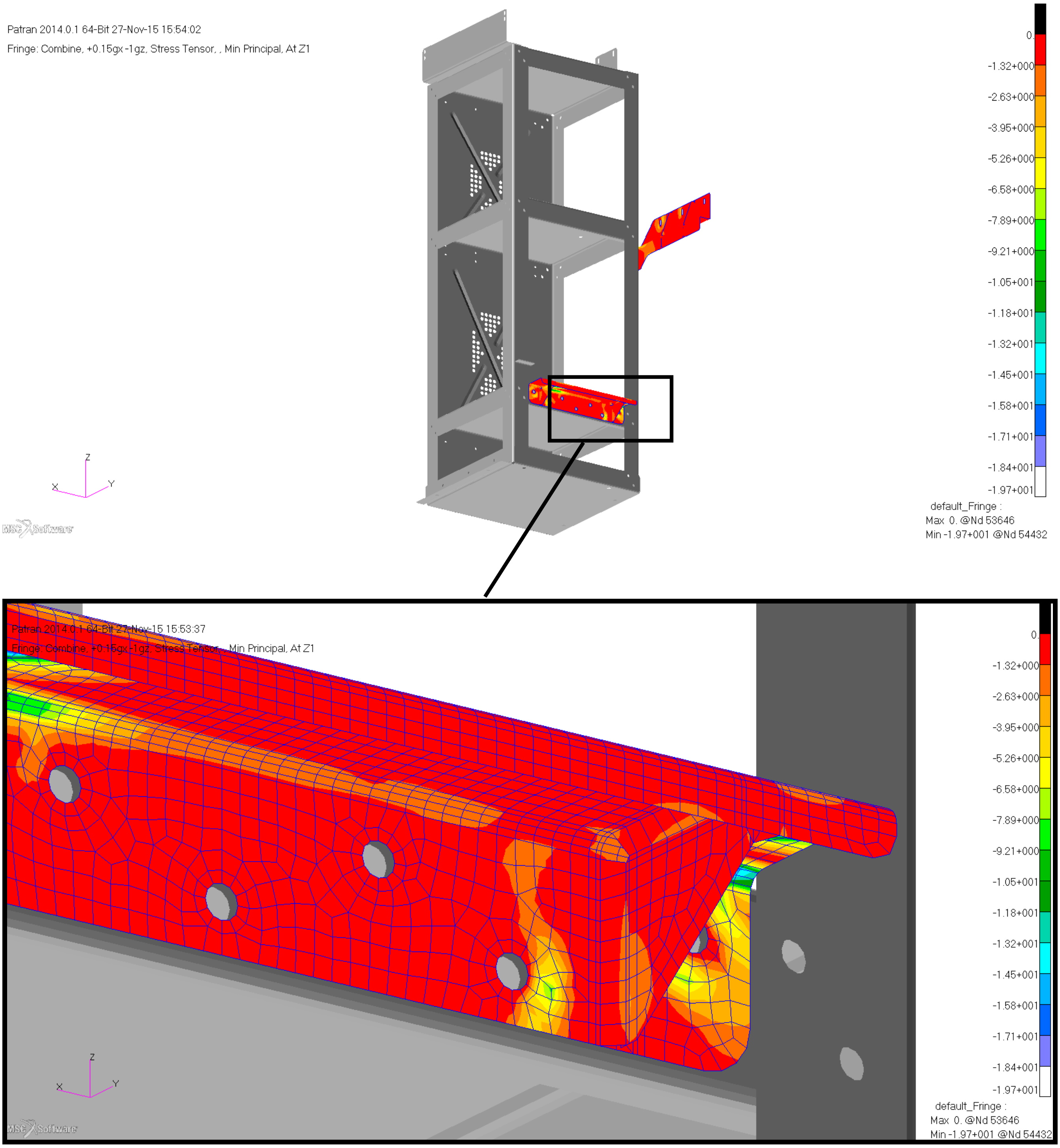

Figure 8.5 – Minimum Principal calculated stress [MPa] for the Longitudinal acceleration (load combination with maximum calculated stress range) on the S355MC fillet weld

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9 Modal analysis results

The first natural frequencies of the model are summarized in the next table.

Mode	Frequency [Hz]	Mode shape
I	22.9	Global Flexural mode
II	24.1	Global Flexural mode
III	26.8	Global Flexural mode

Table 9.1 – Modal analysis result

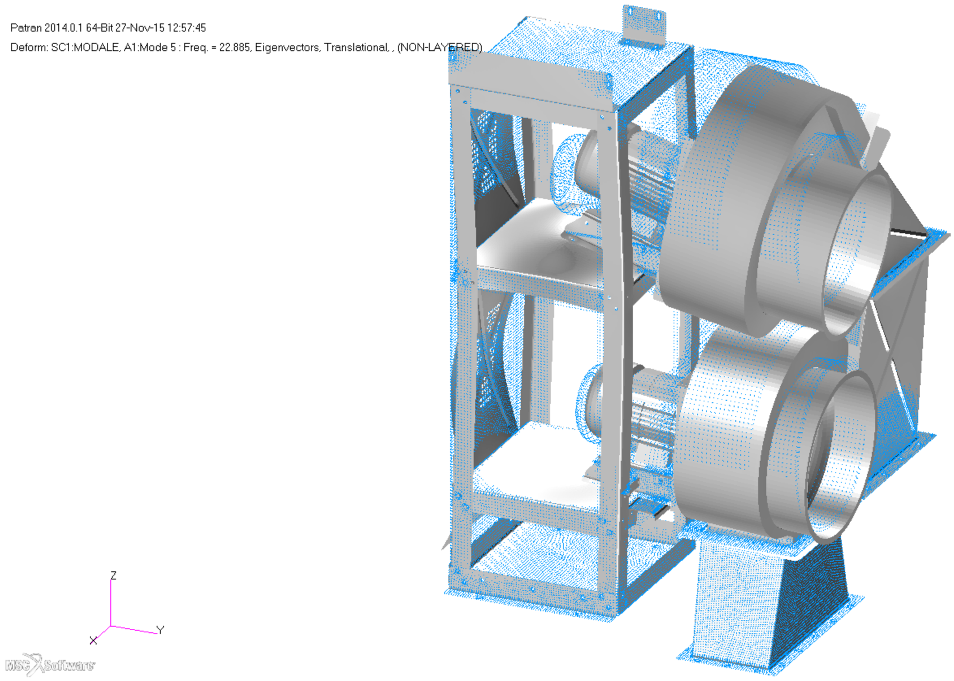

Figure 9.1 – Mode I (22.9Hz) - Global Flexural Mode

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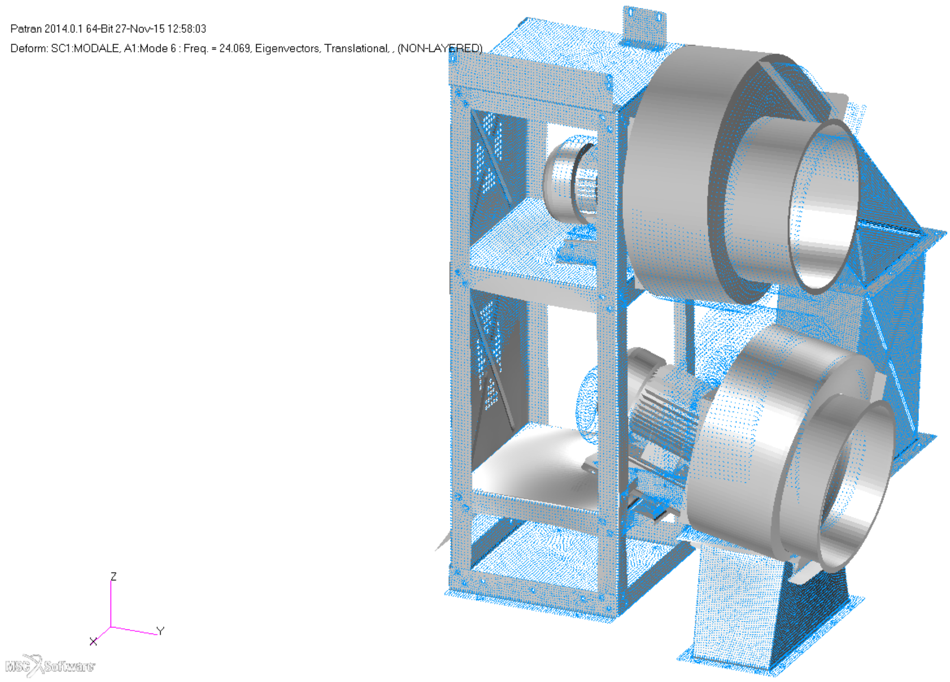

Figure 9.2 – Mode II (24.1Hz) - Global Flexural Mode

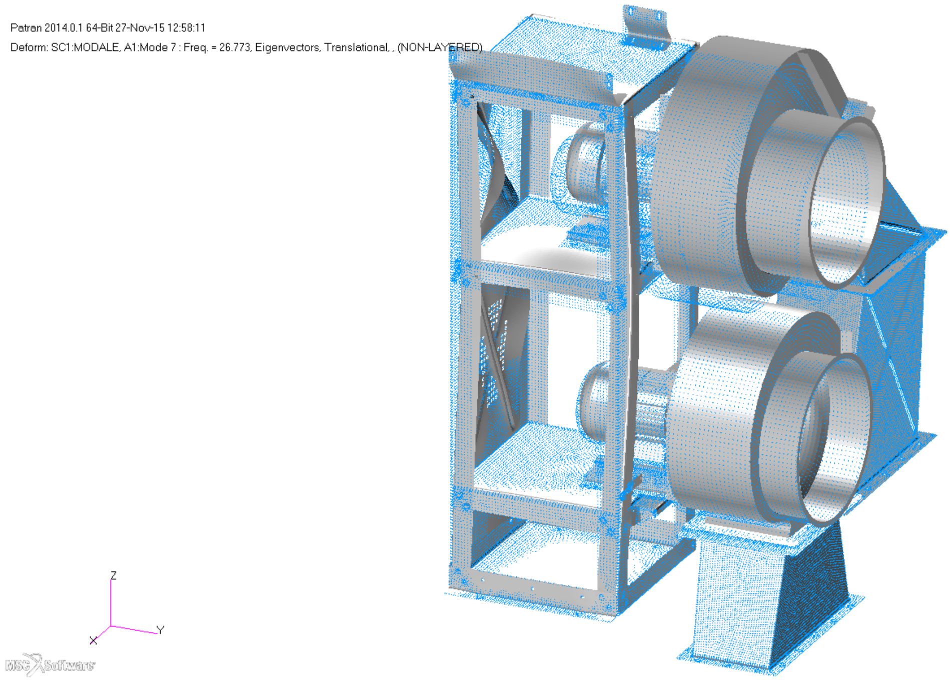

Figure 9.3 – Mode III (26.8Hz) - Global Flexural Mode

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10 Conclusion

The stress analysis of the *TMB System* was carried out. All verifications (Static and Fatigue load conditions) fulfill with requirements.

A modal analysis was then performed and the first global natural frequency of the structure is 22.9Hz.

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Appendix 1

Forces acting on the Bolts

The Table A1.1 summarizes the forces and moments acting on the most stressed bolts for the proof loads. The position of these elements is shown in Figure A1.1. The verification of the bolts is not an aim of this work, and it is responsibility of the Customer.

	Most stressed Bolts and Rivets – Proof Loads								
	Element ID	F_x [N]	F_y [N]	F_z [N]	F_q [N]	M_x [Nmm]	M_y [Nmm]	M_z [Nmm]	M_q [Nmm]
M12	400042	150	9965	-9755	13945	25953	-69	3541	3541
	400080	-4164	-2700	2578	3733	-2892	53792	-3091	53881
	400081	-3464	2317	2007	3066	2882	37190	-2716	37289
M8	300022	199	-1098	-53	1100	-21	-193	41237	41237
	300025	1841	-1537	829	1746	950	-7860	-5145	9395
	300039	4	2140	-910	2325	-234	1288	3110	3366

Table A1.1 – Most stressed bolts, Proof Loads

	Most stressed Bolts – Fatigue Loads								
	Element ID	ΔF_x [N]	ΔF_y [N]	ΔF_z [N]	ΔF_q [N]	ΔM_x [Nmm]	ΔM_y [Nmm]	ΔM_z [Nmm]	ΔM_q [Nmm]
M12	400042	3	558	-578	803	1507	-21	149	151
	400080	-235	-109	129	169	-239	3271	-1905	3785
	400081	-228	98	110	148	237	2811	2101	3510
M8	300021	15	94	-51	107	-9	-172	-2273	2279
	300022	-4	-75	-171	187	68	-63	-69	94
	300025	-106	92	-47	103	-56	463	235	519

Table A1.2 – Most stressed bolts, Fatigue Loads (force and moment range calculated between extreme positions of the fatigue cycle)

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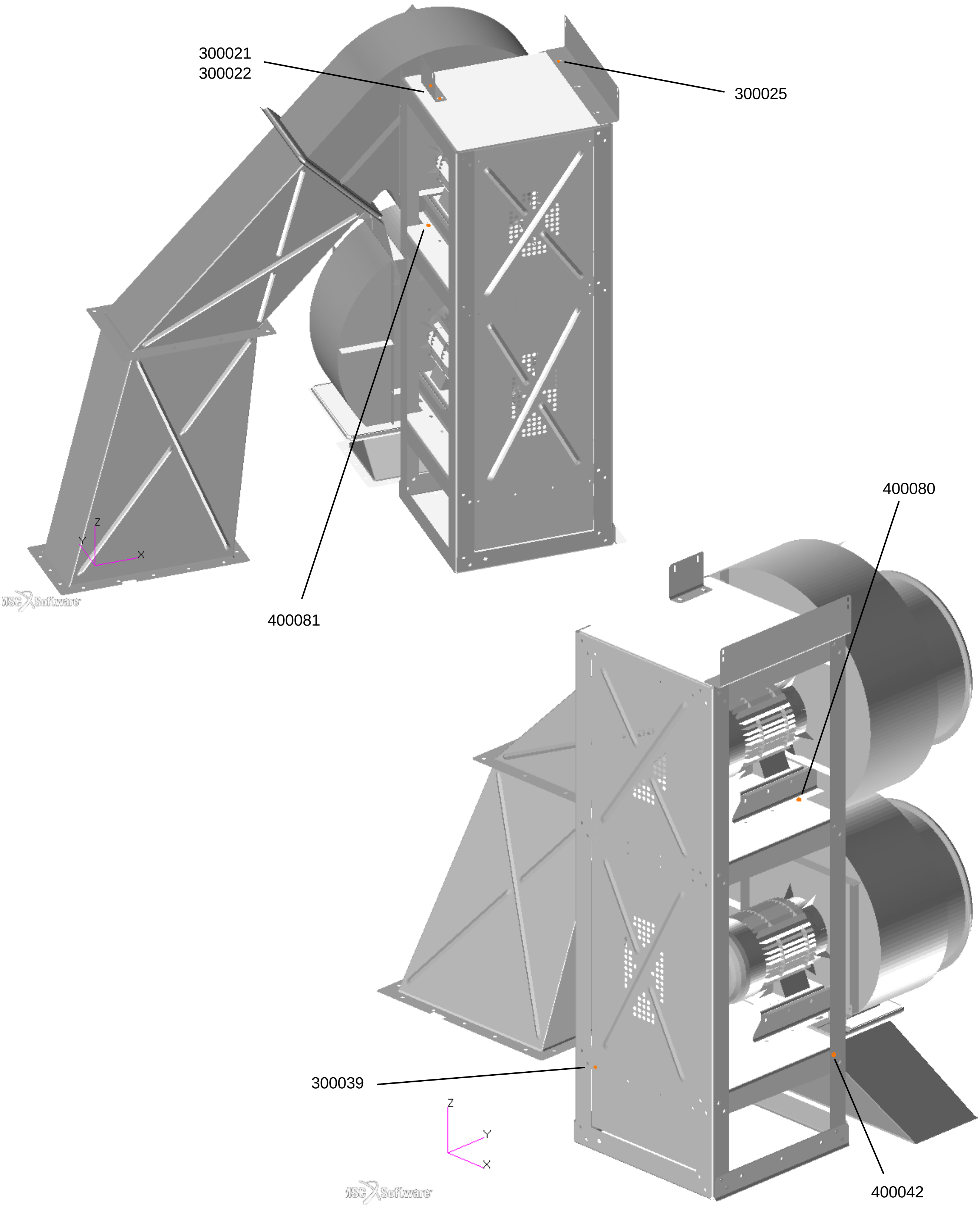

Figure A1.1 – Position of most stressed bolts, Proof and Fatigue Loads

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APPENDIX TO TECHNICAL REPORT N°1319 – 2015

Author	Check	Rev.	Date
L. Orsenigo	A. Ferraris	0	01/02/2016

1. Bolted connection verification

The following verification calculation of the bolted connection has been done according to:

- UNI EN 1993-1-8. Category C.

2. Bolted connection characteristics

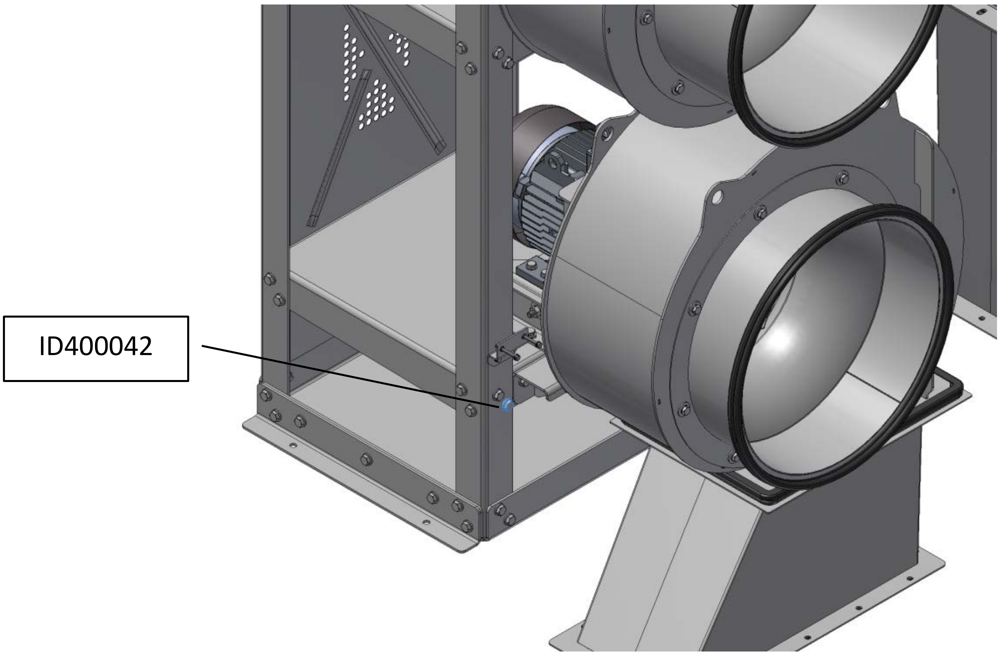
DIM.	ID	CLASS	f_{ub} [N/mm2]	TYPE OF CONNECTION	METAL SHEET 1	METAL SHEET 2	μ_s
M8	300022	A2-70	700	Screw UNI 5739 + Washer // Washer + Washer.UNI1751 + Nut	5mm – Carb. Steel painted	5mm – Carb. Steel painted	0.3
M8	300025	A2-70	700	Screw UNI5739 + Washer // Washer + Washer.UNI1751 + Nut	5mm – Carb. Steel painted	5mm – Carb. Steel painted	0.3
M8	300039	A2-70	700	Screw UNI5739 + Washer + Washer.UNI1751 // Threaded Insert	5mm – Carb. Steel painted		0.3
M12	400080	A2-70	700	Screw UNI5739 + Washer // Washer + Washer.UNI1751 + Nut	5mm – Carb. Steel painted	5mm – Carb. Steel painted	0.3
M12	400081	A2-70	700	Screw UNI 5739 + Washer // Washer + Washer.UNI1751 + Nut	5mm – Carb. Steel painted	5mm – Carb. Steel painted	0.3
M12	400042	A2-70	700	Screw UNI5739 + Washer // Washer + Washer.UNI1751 + Nut	5mm – Carb. Steel painted	5mm – Carb. Steel painted	0.3

3. Calculation results

ID	$F_{v,Ed}$	$F_{t,Ed}$	$F_{p,C}$	$F_{s,Rd}$	$F_{b,Rd}$	$N_{net,Rd}$	$F_{v,Rd}$	$F_{t,Rd}$	$F_{v,Ed} <= F_{s,Rd}$	$F_{v,Ed} <= F_{b,Rd}$	$F_{v,Ed} <= N_{net,Rd}$
300022	1100	199	19190	4567	45900	37275	13159	13817	OK	OK	OK
300025	1746	1841	19190	4252	45900	37275	13159	13817	OK	OK	OK
300039	2325	4	19190	4605	45900	37275	13159	13817	OK	OK	OK
400080	3733	4164	41289	9110	34794	83425	28313	29728	OK	OK	OK
400081	3066	3464	41289	9244	34794	83425	28313	29728	OK	OK	OK
400042	13945	150	41289	9881	28900	83425	28313	29728	NO	OK	OK

4. Conclusion

All the bolted connections pass the verification, with the exception of item 4**00042** that does not pass the verification $\mathbf{F_{v,Ed} <= F_{s,Rd}}$.



The solution proposed is to use a bigger Bolt M14 instead of M12, and to use a bolt with higher class strength (for example a class A2-80).

ID 400042 A : M14 bolt class A2-70
ID 400042 B : M14 bolt class A2-80

ID	$F_{v,Ed}$	$F_{t,Ed}$	$F_{p,C}$	$F_{s,Rd}$	$F_{b,Rd}$	$N_{net,Rd}$	$F_{v,Rd}$	$F_{t,Rd}$	$F_{v,Ed}$ <= $F_{s,Rd}$	$F_{v,Ed}$ <= $F_{b,Rd}$	$F_{v,Ed}$ <= $N_{net,Rd}$
400042 A*	13945	150	56564	13547	27653	37275	38787	40726	NO	OK	OK
400042 B*	13945	150	64645	15486	27653	37275	44328	46544	OK	OK	OK

The Item id 400042 A does not pass the verification $\mathbf{F_{v,Ed} <= F_{s,Rd}}$, because 13945 is higher than 13547 even if only 398N more.