Technical note
Bonus assignment 3
Delfi-n3Xt STS

Spacecraft Structures
Ae4-537

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1. Introduction

During the launch large forces are experienced by a satellite. These forces put great loads on both the instruments as well as the structure of the satellite. For the satellite to fulfil its mission properly the deformations due to the launch loads should not be too large.

Doing structural tests with a real model of a satellite is a very expensive way to determine the deformation within the structure. Another way to verify the structure can withstand the forces suffered during the launch is using a finite element analysis. With this method the loads in the model are calculated with the help of a computer. The big upside of testing this way is that less material and recourses are needed, while still the design can be tested.

In this technical note the results of a finite element analysis of the structure of Delfi-n3Xt are presented. The FEA is done in the program Abaqus. The different load types which occur during the launch of the satellite are considered and the responses are calculated in the finite element model. Also a minimal thickness for the walls and different materials are considered.

In chapter 2 the set up of the model is described. Chapter 3 elaborates on the different load cases acting on the satellite during launch. Chapter 4 shows the results of the analysis. Chapter 5 contains the optimization of the wall thickness. The conclusions and recommendations are given is chapter 6.

2. Finite Element Model

Before a finite element analysis can be done first a good model has to be defined. The model is built up from several components, which represent the components of the satellite in real life. Every component also needs to have a material appointed to ensure that the properties of the satellite resemble the real satellite as close as possible. Every component is also broken up into smaller pieces to form a mesh.

In this chapter these building blocks are explained a bit more.

2.1. Components

The model is based on the CATIA drawing existing for the Delfi-n3Xt. The model is simplified to make the simulations faster, while keeping as close as possible to the real situation.

The different PCBs have been replaced by flat plates with the density adapted to give them the right mass for the weight distribution of the satellite. The MPS is modelled as a block, with its centre of mass the same location as specified in the volume budget of the Delfi-n3Xt. Also the densities of the TOP and BOP are adapted to fit the mass stated in the volume budget.

All small holes for connecting the different components have been removed. This has been done to counter stress concentrations around those holes, which could disturb the loads on the rest of the structure. That way also the mesh could be made less dense and the computation is a lot faster. The larger holes, e.g. for the booster or the MPS, are still in the model.

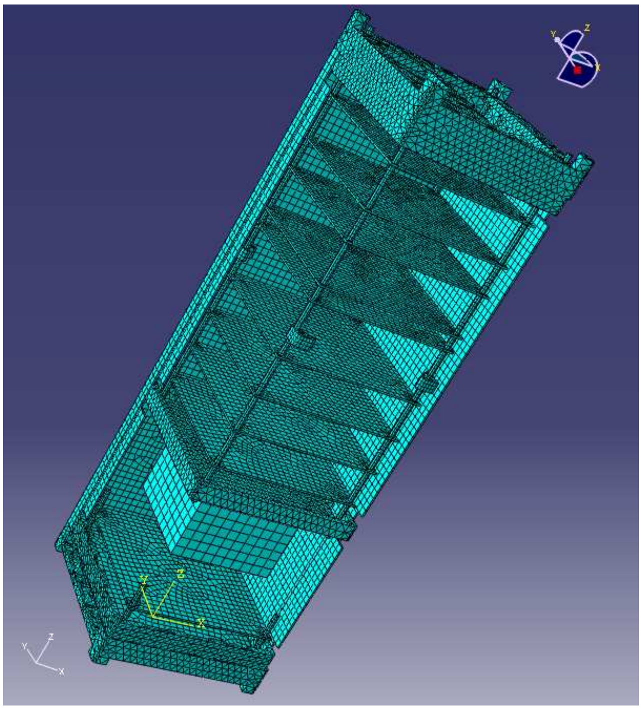

Figure 2.1: The fem model with the mesh applied

2.2. Materials

The material used for the structure (the TOP, BOP, IP, the rods and the walls) and the MPS was chosen to resemble a material based on Aluminium, this has a tensile strength of 72 GPa, and a yield stress of 400 MPa. The density is adapted to fit the masses stated in the volume budget. The densities can be found in table 2.1. For the PCBs a material was created with a tensile strength of 300 GPa, to make the influence of the PCBs as small as possible. Here the densities are to be found in table 2.1. In the model all PCB components are combined into one component with a mass and centre of gravity equal to the separate subsystems to speed up the computations, while reducing the effect on the actual simulation. The difference between the actual mass in the volume budget and the mass of the model is due to the difference between the volume·density of the model and that of the actual mass.

Component	Density* [kg/m^3]	Actual mass [kg]	Model mass [kg]	Material
BOP	3274	0.127		Aluminium
MPS	3592	0.587		PCB
IP	2756	0.075		Aluminium
TCB		0.045		PCB
VHF AB		0.124		PCB
ITRX		0.124		PCB
STX		0.124		PCB
T^{3}mPS		0.162		PCB
PTRX	19765	0.124		PCB
ADCS electronics		0.078		PCB
ADCS RW		0.204		PCB
OBC		0.132		PCB
EPS electronics		0.065		PCB
EPS Batteries		0.343		PCB
TOP	8181	0.372		Aluminium
STS	2800	0.858		Aluminium
		3.502	3.066	$z_{c.g.}$ = 179.67 mm

* Not necessarily the density of the actual material

Table 2.1: Masses, materials and "densities" of all the different components

2.3. Elements

Each component is build up from a large number of cubes and tetrahedrons. The total model is build up of 41538 elements, connected by 36171 nodes resulting in 108513 degrees of freedom.

3. Load cases

For the before testing the model it is important to know what kind of loads will be on the structure and how large they will be. The magnitudes of the forces are mainly determined by the launcher and the arrangement of the satellite in the launcher.

In this section the selection of the launcher is treaded and the loads on the satellite are stated.

3.1. Launcher selection

A number of the most common launchers for small satellites where compared for selecting the proper launch loads for the simulation. The loads for most launchers are very comparable, with only small differences in accelerations in longitudinal and lateral directions. After comparing the Ariane 5, Vega, Soyuz and PSLV launchers, the PSLV was selected because it has the highest launch loads giving the worst case scenario. Delfi-n3Xt's predecessor, Delfi-C^3, was launched by a PSLV as well.

3.2. Loads

The loads on a satellite during launch can roughly be divided in four different categories: Quasi-static loads, sinusoidal loads, random loads and shock loads. All loads can be also be different in longitudinal and lateral directions.

4.1.1. Quasi-static loads

Quasi-static loads are the loads due to the acceleration of the satellite while being launched. During launch the acceleration increases, since the mass of the launch vehicle decreases. Steady-state accelerations in the longitudinal directions are usually much larger then those in the lateral direction.

For an auxiliary satellite on the PSLV the maximum quasi-static loads are

Longitudinal acceleration (Static + Dynamic): + 7/-2.5 g
Lateral acceleration (Static + Dynamic): ± 6g

4.1.2. Sinusoidal loads

Sinusoidal loads are low frequency (5-100 Hz), dynamical, mechanical loads due to interactions between the launcher and the spacecraft.

The PSLV user's manual gives the test levels in table 3.1.

Sine vibration test levels			
	Frequency Range (Hz)	*Qualification level*	*Acceptance level*
Longitudinal axis	4-10	10 mm (0 to peak)	8 mm (0 to peak)
	10-100	3.75 g	3 g
Lateral axis	2-8	10 mm	8 mm
	8-100	2.5 g	2 g
Sweep rate		2 Oct/min	4 Oct/min

Table 3.1: Sine Vibration test levels

4.1.3. Random loads

Boundary layer turbulence and acoustic loads translated to random vibrations which also act on the spacecraft during launch.

The random vibration test levels for the PSLV are given in table 3.2.

Random vibration test levels		
Frequency	*Qualification PSD (g^2/Hz)*	*Acceptance PSD (g^2/Hz)*
20	0.002	0.001
110	0.002	0.001
250	0.034	0.015
1000	0.034	0.015
2000	0.009	0.004
G_{rms}	6.7	4.47
Duration	2 min/axis	1 min/axis

Table 3.2: Random vibration test levels

4.1.4. Shock loads

During separation of stages from the launch vehicle very short duration loads are put on the internal structure of the spacecraft. The frequencies of these shock are often much higher then the fundamental frequencies of the satellite.

For the PSLV the typical shock spectrum is shown in figure 3.1.

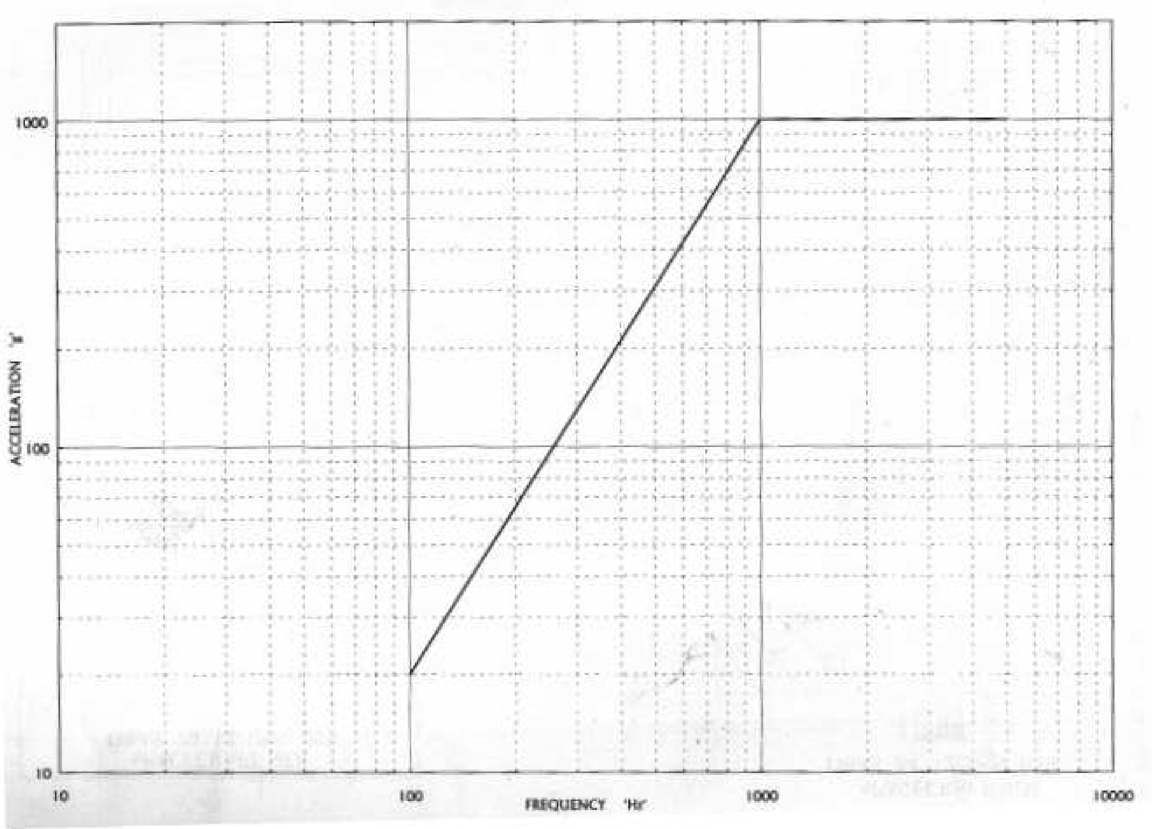

Figure 3.1: Typical shock loads for auxiliary satellites on the PSLV

3.3. Safety factors

Because there are always uncertainties in the exact forces in the launch loads due to numerous varying conditions in the flight and in the spacecraft.

For the quasi-static loads a safety factor of 1.25 is required by the launcher for the design check.

For the sinusoidal and random loads the safety factors are already included in the qualification level and the acceptance level.

3.4. Other requirements

The fundamental frequency in the longitudinal axis for the PSLV is required to be >90 Hz. In the lateral direction the fundamental frequency needs to be >45 Hz.

4. Results

In this chapter the results for the different load cases are described and some of the problems which occurred are stated.

The model is completely constraint at the feet on the bottom panel. All longitudinal loads are applied at the feet of the top panel. The total area of the feet has been estimated to be 55 mm^2 per foot. All lateral loads are applied to the side of the top panel, with an area of 1400 mm^2.

In all cases a pressure load of about 20 kg (196 N) is put on the structure as a result of the spring in the deployer, as requested by ir. G.F. Brouwer.

4.1. Quasi-static loads

Quasi-static loads are the easiest loads to understand. These loads are just due to the acceleration of the launcher and do not vary very quickly.

4.1.1. Positive longitudinal load

In the user manual a positive acceleration of 7g is given. With a safety factor of 1.25 this leads to a load of 8.75g For a satellite of 3.5 kg this leads to a total force of about 300 N or a load of 1.37 MPa on the feet.

In Figure 4.1 the stresses due to the loads are displayed. All Mises stresses are below 1 MPa, most of them even below 0.5 MPa.

4.1.2. Negative longitudinal load

In the negative direction loads of -2.5g are specified, with a safety factor this becomes -3.125g. These lead to a force of -108 N or a load of 0.49 MPa.

In Figure 4.2 the stresses due to the loads are displayed. The magnitude of the deformations is a little bit smaller than those in the positive load case.

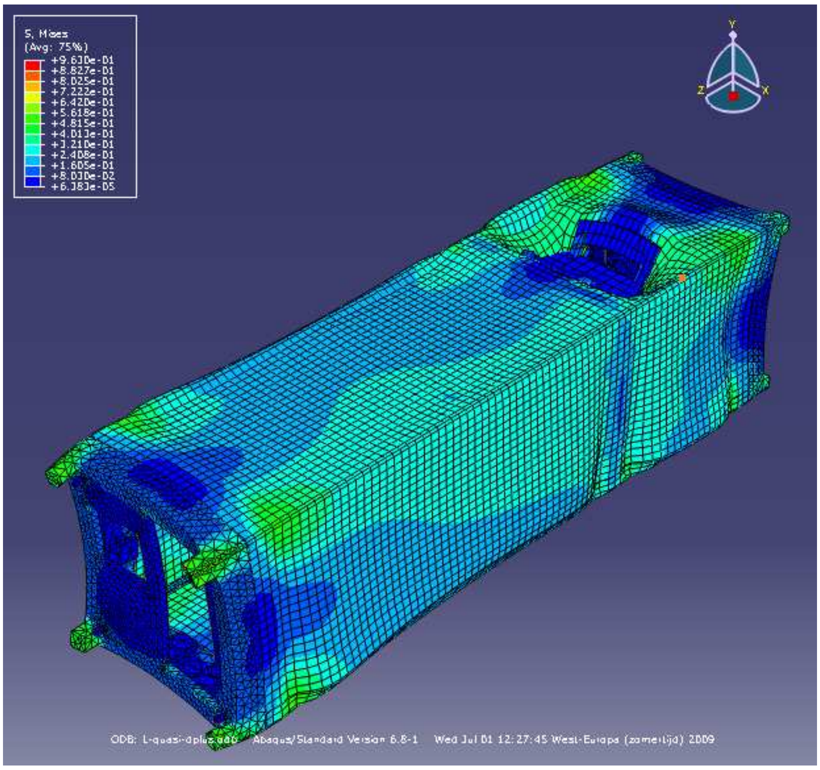

Figure 4.1: Stresses due to positive quasi-static longitudinal loads

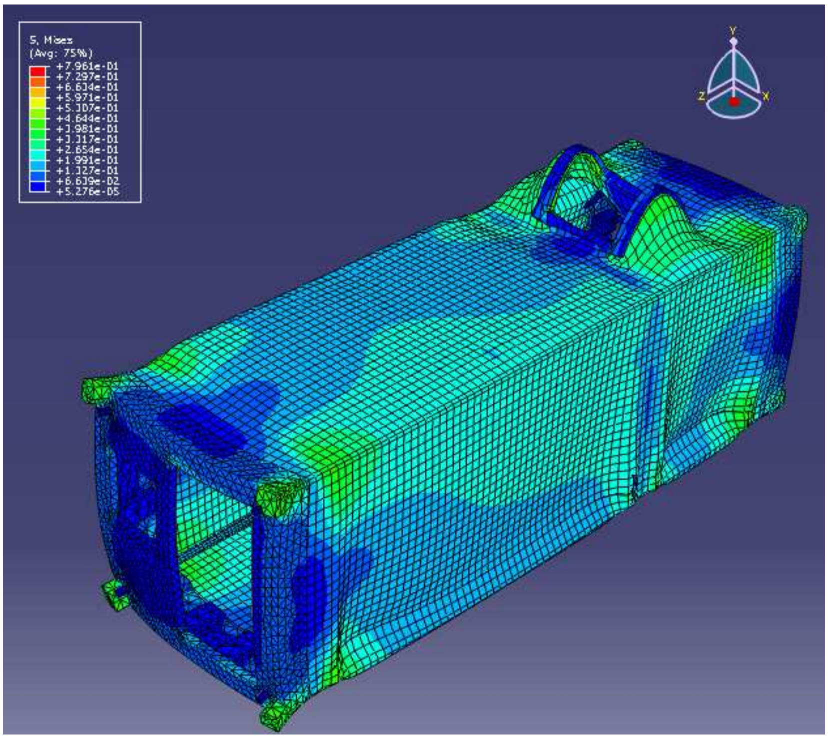

Figure 4.2: Stresses due to negative quasi-static longitudinal loads

4.1.3. Lateral load

For the lateral case a pressure has been put on the side of the top panel. The maximum lateral acceleration for auxiliary satellites is given to be ±6g by the user manual. With the safety factor and spacecraft mass this leads to a force of ±259 N or a pressure of ±0.185 MPa.

In this case most deformations appear in the lower parts of the satellite. The size of the Mises stress is in the order of 1 MPa.

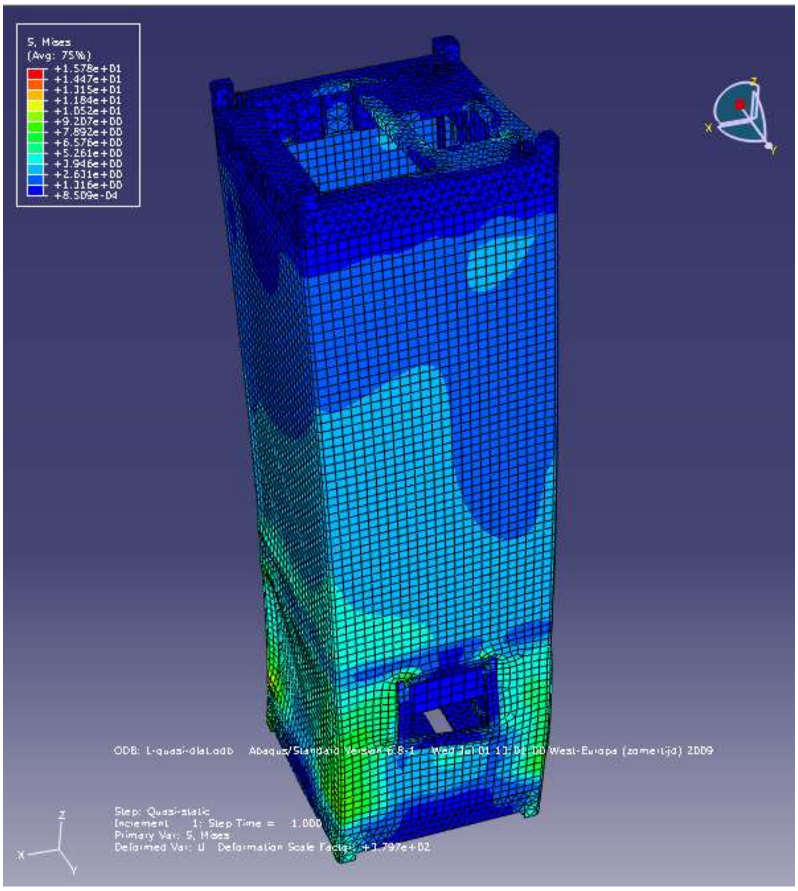

Figure 4.3: Stresses due to quasi-static lateral loads

4.2. Sinusoidal loads

The loads occurring in the sinusoidal load case are a bit lower then in the quasi-static case and also because the periodic loads of the random loads are much larger then the random loads. No serious problems with deformations due to sinusoidal loads are expected.

4.3. Random loads

The maximal loads occurring due to random vibrations are often significant to those in the quasi-static a longitudinal case. The reaction force due to a random load can be calculated by

$$F_{reaction} = 3 \cdot m \cdot \sqrt{\frac{\pi}{2} f_0 Q W(f_0)} \tag{4.1}$$

Here, f_0 is the central frequency, Q is the dampening coefficient and $W(f_0)$ the PSD at f_0. In Table 3.2 it can be seen that the highest forces appear at a frequency of 1000 Hz, the PSD at that point is 0.034 g^2/Hz. When assuming a dampening coefficient of 10 and a mass of 3.524 kg a reaction force of

$$F_{reaction} = 3 \cdot 3.524 \cdot \sqrt{\frac{\pi}{2} 1000 \cdot 10 \cdot 0.034} = 244.32N$$

This leads to a pressure of 1.11 MPa on the satellite feet. No safety factor is needed, since the loads are at qualification level.

Figure 4.4 and Figure 4.5 show the stresses due to random load forces. All loads are again well below the yield stress.

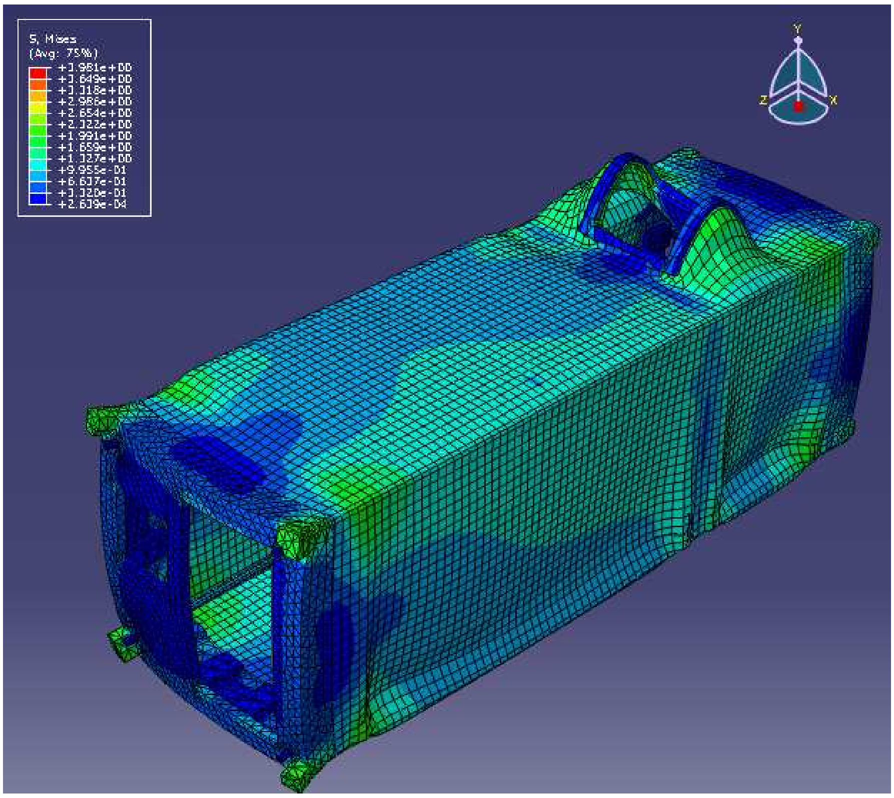

Figure 4.4: Stresses due to maximum random vibration forces, push

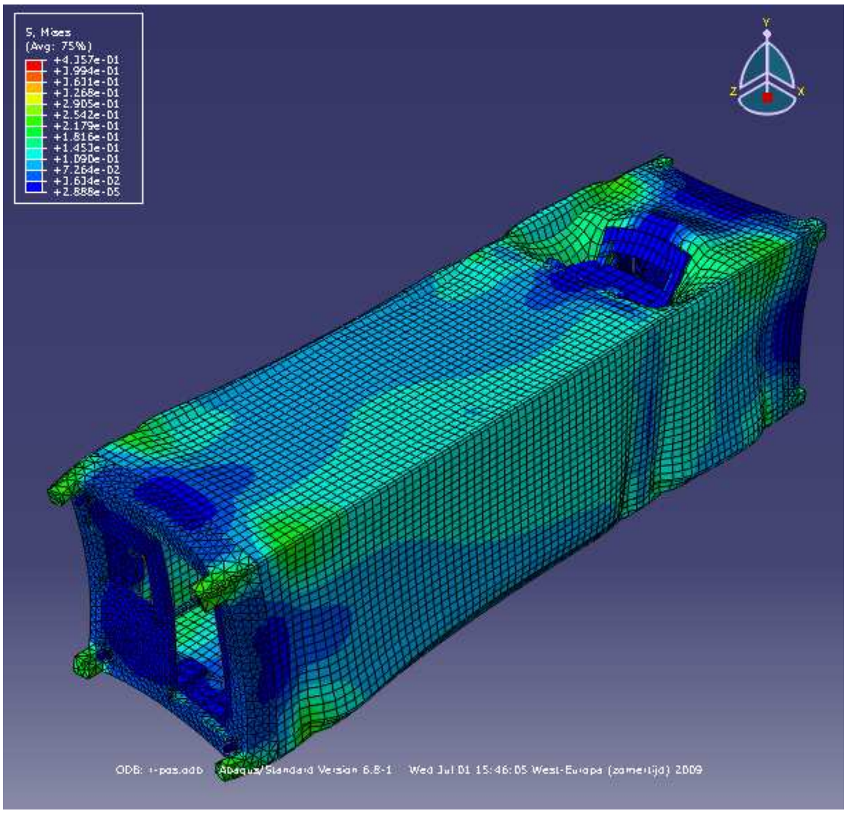

Figure 4.5: Stresses due to maximum random vibrations, pull

4.4. Shock loads

The final type of load is the shock loads. These are very high frequency very high loads. The largest loads appearing during the launch are 1000g. This leads to a load of 157 MPa on the feet of the satellite.

With a load of 1000g the stresses in the structure locally reach 312 MPa for both push and pull, this is still below the yield stress of aluminium. So even in case of shock loads the structure of the satellite will not fail.

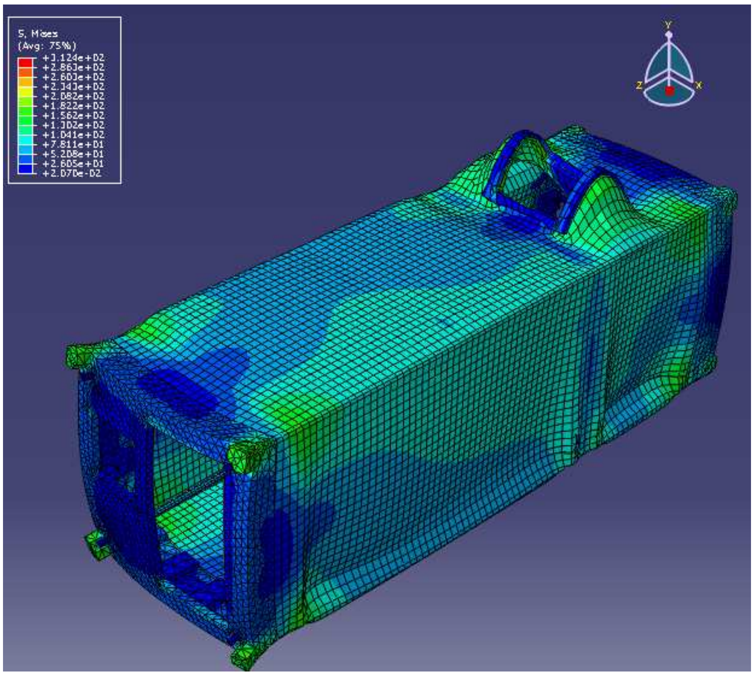

Figure 4.6: Stresses due to 1000g push

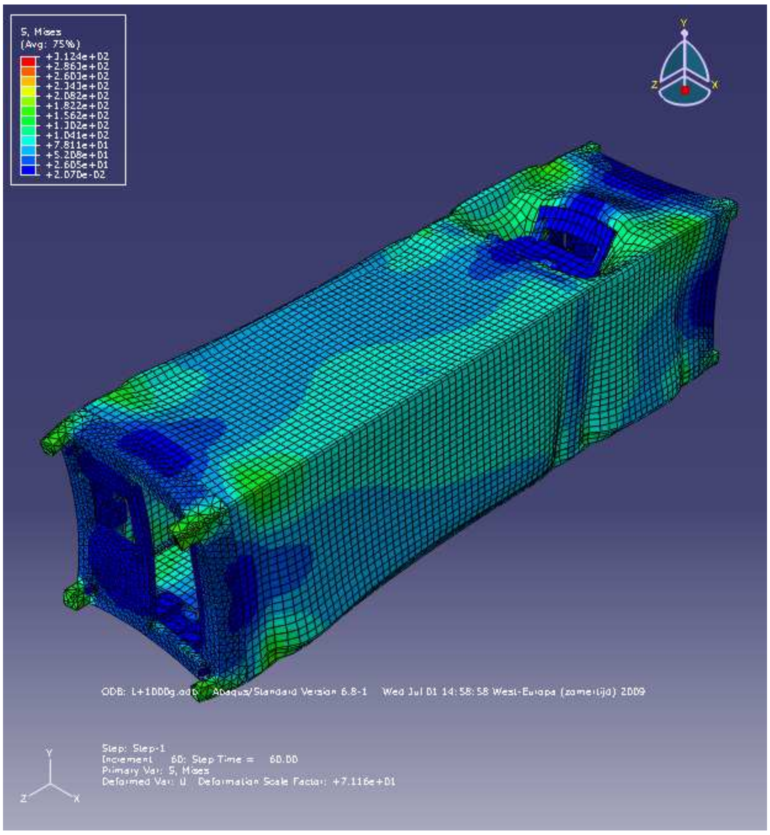

Figure 4.7: Stresses due to 1000g pull

4.5. Eigen frequency

When a structures gets vibrated in its eigenfrequency resonation can occur, which can lead to very destructive results. FEM programs also need to calculate the eigenfrequencies before they can do a frequency sweep. A list of the first 50 of a total of 1139 uptil 8000 Hz can be found in Appendix A.

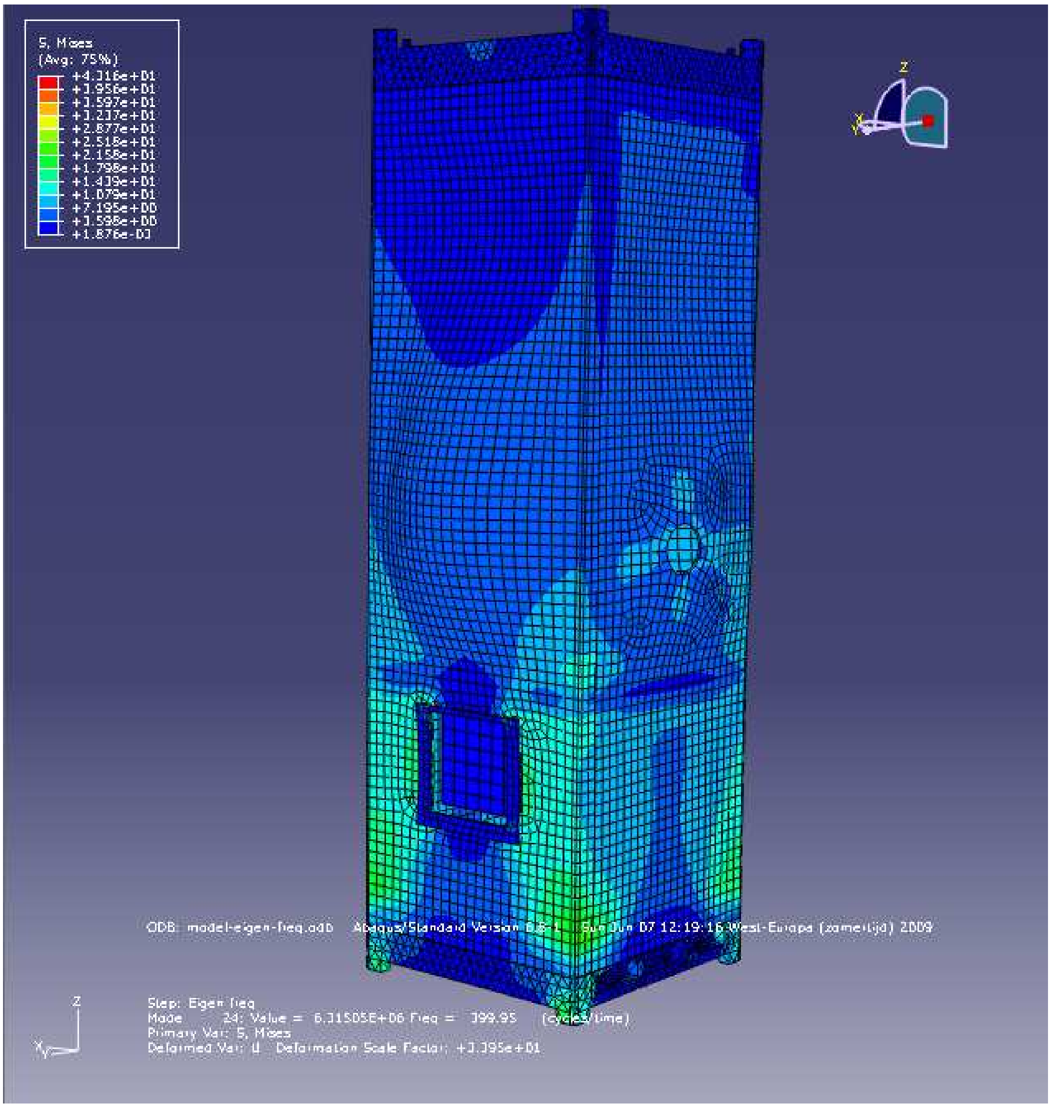

Figure 4.8: Example of an eigenmode where the deformation starts is clearly visible

5. Optimization

Bringing material into space is a very expensive activity. Therefore it is desirable for the satellite to be as light as possible. The structure of the spacecraft is usually one of the heaviest components for small satellites, so it is a very attractive part to save weight.

The highest loads on the structure took place at the shock loads of 1000g. These loads resulted in a stress of 312 MPa locally, for a very small time. Because plastic deformation is not preferred, the maximal loads on the structure should stay below the yield load of 400 MPa.

With a wall thickness of 1 mm the cross section of the satellite in the xy-plane is about 40 mm^2. The force going through that surface at 312 MPa is $\sigma \cdot A = 312 \cdot 400 = 124800$ N. For the same force to have a stress of 400 MPa a wall thickness of 0.78 mm is required. The volume saved over the entire satellite is $t_s \cdot l \cdot h = 0.22 \cdot 400 \cdot 302 = 26576\ mm^3$. At a density of 2800 kg$\cdot$m^3 the saved mass adds up to 0.074 kg = 74 g, about 2% of the satellite’s mass.

Of course, there are also more things to be taken into account when choosing the proper wall thickness for a satellite, e.g. handling, manufacturability and interfaces with other parts of the satellite.

6. Conclusions and recommendations

The goal of this practical was to create a FEM model for the Delfi-n3Xt and to verify the satellite was able to withstand the loads excited on the structure during launch.

All loads working on the structure have been gathered in lesser or bigger extend and put on the model. Eventually it turned out the structure was well able to handle all the loads, without big problems and failures in the structure.

It has been found there is still some room for optimisation in the structure, which could lead to saving some of the weight of the satellite. Changing the wall thickness could have a negative effect on the other qualifications of the satellite, though.

The biggest problems in the practical occurred while trying to test the random and sinusoidal loads. The program chosen to work with turned out not to be able to handle PSDs and varying frequencies very well. In these cases a more simplified approach has been used by neglecting the oscillation effects and just treating the loads as they were discrete. Even in these simplified cases the satellite structure was able to handle the loads put on it.

Another big problem was that FEM is no longer part of the Bachelor's curriculum, which leads to the fact that students have little to no experience using FEM-programs, let alone on such a complex problem. It would be recommendable to have a larger introduction into using this kind of program during the course, since it is an important part of the work a structural engineer does in industry.

Sources

[1] Wijker, J.J., 2008, *Spacecraft structures*, Springer, ISBN 978-3-540-75552-4

[2] 2008, *Abaqus Documentation*, Version 6.8, Dassault Systems Simulia

[3] Narayana Moorthy, N. and Ramakrishnan, S., March 2005, *Polar Satellite Launch Vehicle User's Manual*, issue 4, Indian Space Research Organisation

[4] Ariane Space, 2006, 2006, 2008, *User's Manual Soyuz, Vega, Ariane 5*, www.arianespace.com

[5] Go, S.Y., March 2009, *Delfi-n3Xt Volume Budget, Appendix Calculation*, version 1.2, TU Delft

Appendix A: First 50 eigenvalues of the model

In the list below the output of Abaqus for the calculation of the eigenvalues of the system up to about 625 Hz. The complete list of the 1139 eigenvalues up to 8000 Hz can be found in the data file.

E I G E N V A L U E   O U T P U T

MODE NO	EIGENVALUE	FREQUENCY (RAD/TIME)	FREQUENCY (CYCLES/TIME)	GENERALIZED MASS (tonne)	COMPOSITE MODAL DAMPING
1	12873.	113.46	18.058	5.35980E-04	0.0000
2	34993.	187.06	29.772	1.64494E-04	0.0000
3	97910.	312.91	49.801	2.46194E-04	0.0000
4	1.40507E+05	374.84	59.658	1.50530E-03	0.0000
5	2.42126E+05	492.06	78.314	1.36791E-04	0.0000
6	2.46348E+05	496.33	78.994	3.70135E-04	0.0000
7	4.65140E+05	682.01	108.55	1.68912E-04	0.0000
8	6.03322E+05	776.74	123.62	2.07594E-04	0.0000
9	8.21858E+05	906.56	144.28	2.32565E-04	0.0000
10	1.30765E+06	1143.5	182.00	1.50542E-04	0.0000
11	1.58206E+06	1257.8	200.19	2.10316E-04	0.0000
12	1.78472E+06	1335.9	212.62	7.57813E-05	0.0000
13	1.98064E+06	1407.4	223.99	1.23406E-05	0.0000
14	2.02200E+06	1422.0	226.31	2.06314E-04	0.0000
15	2.25867E+06	1502.9	239.19	2.02306E-05	0.0000
16	2.45896E+06	1568.1	249.57	2.36790E-05	0.0000
17	2.70273E+06	1644.0	261.65	2.39617E-05	0.0000
18	2.90375E+06	1704.0	271.21	1.60317E-04	0.0000
19	3.14375E+06	1773.1	282.19	4.70072E-05	0.0000
20	3.15054E+06	1775.0	282.50	1.30361E-05	0.0000
21	3.92213E+06	1980.4	315.20	1.14844E-04	0.0000
22	4.05207E+06	2013.0	320.38	1.84294E-04	0.0000
23	5.26480E+06	2294.5	365.18	1.09543E-04	0.0000
24	6.31505E+06	2513.0	399.95	3.00436E-05	0.0000
25	6.46462E+06	2542.6	404.66	1.22363E-04	0.0000
26	6.73232E+06	2594.7	412.95	2.12807E-05	0.0000
27	6.86399E+06	2619.9	416.97	7.96103E-05	0.0000
28	7.22463E+06	2687.9	427.79	1.10196E-04	0.0000
29	7.41005E+06	2722.1	433.24	1.72981E-05	0.0000
30	7.56830E+06	2751.1	437.84	2.32519E-05	0.0000
31	7.71407E+06	2777.4	442.04	1.13850E-05	0.0000
32	8.51648E+06	2918.3	464.46	1.12867E-05	0.0000
33	8.93971E+06	2989.9	475.86	5.99546E-05	0.0000
34	8.97817E+06	2996.4	476.89	2.44657E-05	0.0000
35	9.04599E+06	3007.7	478.68	1.90259E-05	0.0000
36	9.08124E+06	3013.5	479.62	3.58984E-05	0.0000
37	9.67680E+06	3110.8	495.09	5.37112E-06	0.0000
38	9.71065E+06	3116.2	495.96	1.87444E-04	0.0000
39	9.86434E+06	3140.8	499.87	1.79384E-05	0.0000
40	1.08285E+07	3290.7	523.73	1.17397E-04	0.0000
41	1.20991E+07	3478.4	553.60	1.85909E-04	0.0000
42	1.28358E+07	3582.7	570.21	2.16103E-05	0.0000
43	1.29654E+07	3600.7	573.08	7.51992E-06	0.0000
44	1.36119E+07	3689.4	587.19	9.97787E-05	0.0000
45	1.36411E+07	3693.4	587.82	5.13345E-06	0.0000
46	1.40586E+07	3749.5	596.75	2.45016E-05	0.0000
47	1.45260E+07	3811.3	606.59	1.29614E-05	0.0000
48	1.48878E+07	3858.5	614.09	6.45684E-06	0.0000
49	1.49185E+07	3862.5	614.73	1.05886E-04	0.0000
50	1.54348E+07	3928.7	625.27	2.65814E-05	0.0000

Etc. etc.