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Title

Frangibility study of the Normeka AmpliSafe Single Triangle Mast

Summary

The frangibility, as described by the ICAO: Aerodrome design Manual [Part 6, First edition – 2006], of the "AmpliSafe Single Triangle Mast" from Normeka AS has been calculated. The frangibility study has been carried out using the finite element software LS-DYNA. Two heights of the mast are simulated; 2.9 m and 4.9 m.

The frangibility test has two acceptance criteria: The peak force level shall be below 45 kN and the absorbed energy shall be less than 55 kJ.

The main conclusion from the calculation was:

"The results of the calculations are that both the energy criterion and the "peak force"-criterion are fulfilled for both mast heights".

Please also read Section 7.1 on the validity of the results.

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1 Scope of Work

In this work the frangibility, as described by the ICAO: Aerodrome design Manual [Part 6, First edition – 2006] [1], of the "AmpliSafe Single Triangle Mast" from Normeka AS has been calculated.

The frangibility study has been carried out using the finite element software LS-DYNA.

2 Normeka AmpliSafe Single Triangle mast finite element model

The FE model of the Normeka AmpliSafe Single Triangle mast is based on CAD geometry in STEP-format, provided by Normeka AS, labelled "AmpliSafe single mast.STEP" [2]. Two heights of the mast are simulated; 2.9 m and 4.9 m. The mast is bolted to a 20 mm thick aluminium foot plate. The dimension of the attachment bolts is M10x100. The profile of the mast is three sided with a side length of 190 mm. The masses of the models are 16.5 kg for the 2.9 m model and 27.9 kg for the 4.9 m model.

The AmpliSafe Single Triangle mast is modelled using both shell and beam elements, see Figure 1 and Figure 2. The foot plate is modelled with solid elements; the top plate is modelled with shell elements; and the attachment bolts are modelled with beam elements. The element size in the mast-model is between 7 mm and 10 mm. The attachment between the bolts and the mast is rigid, i.e. modelled with nodal rigid bodies.

The clamping points in the corners, that prevents sliding between the corner components, are modelled as spot welds. The distances between the clamping points are 28 mm. To determine the strength of the spot welds, a simulation of a test according to [3] was performed. The simulation of this test is presented in Appendix C.

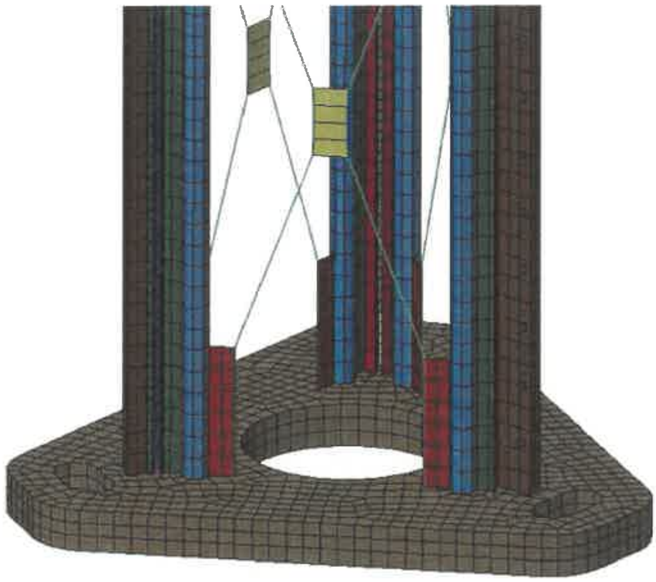


Figure 1: Foot plate and lower part of the AmpliSafe Single Triangle mast.

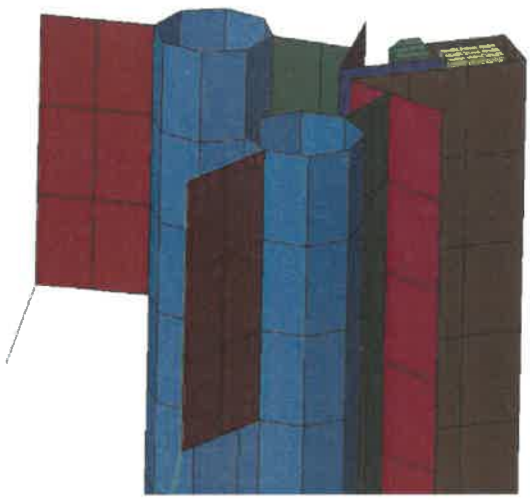


Figure 2: Corner model of the AmpliSafe Single Triangle mast.

An elasto-plastic material model is used for all materials in the AmpliSafe Single Triangle mast-simulation model. No material failure is included in the finite element model, including the bolts.

A summary of the component materials is given in Table 1. The hardening curve used for the main material in the mast, i.e. Al 6063 T6, is shown in Figure 3.

Table 1: Summary of component materials in the Single triangle mast model

Component	Material	Min. yield strength [MPa]
AmpliSafe Single Triangle mast	6063 T6[1]	160
Footplate	6082 T651/62[2]	240
Attachment bolts	Bumax M10 10.9[3]	900

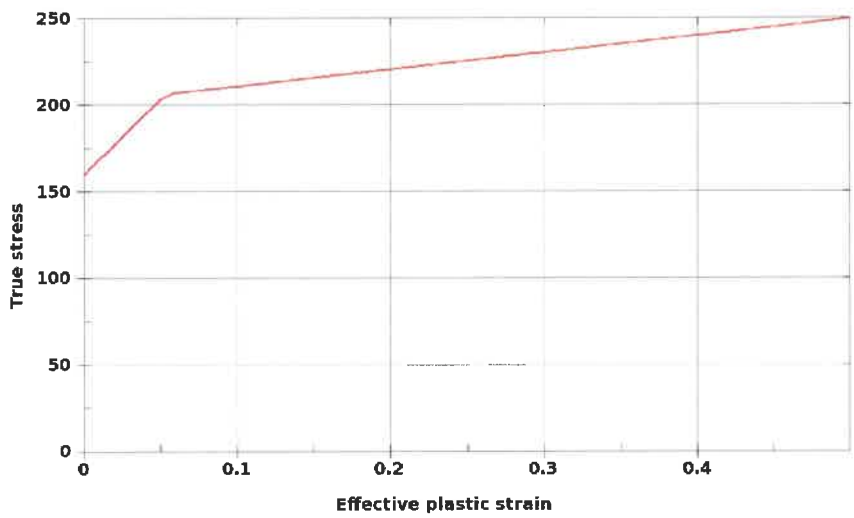


Figure 3: The hardening curve used for the aluminum 6063 T6 material that the mast is made of.

3 Finite element model of NLR Wing impact specimen

The FE model of the wing used in this project is the same model used in project P12007 [4].

The simulation model of the wing is based on drawing "NLR-Wing Impact Specimen" [5] provided by Normeka AS. The total mass of the wing, i.e. including support structure and vehicle, is 3000 kg. The weight of the wing itself is about 50 kg and the weight of the support structure and vehicle is about 2950 kg.

The wing is modeled according to the referenced drawing [5] of a Beech Queen Air wing, supplied by National Aerospace Laboratory, Netherland through Normeka AS. The wing profile model is, basically, a rivet joined aluminum box structure that is mounted to a steel frame.

[1] Ref. SKMBT_C20312022216100.pdf, received from Normeka [6]
[2] Ref. Eurocode 9 EN 1999-1-1:2007
[3] Ref. Bumax certificate (date 100914) supplied by Normeka AS

Figure 4 and Figure 5 shows the wing-model. The grey colored area is the aluminum box structure; the green colored area is the steel frame; the yellow area represents the mounting to the support structure (where load cells are placed in the physical wing); blue area represents the support structure and the brown area represents the vehicle to which the wing is attached in the test. The support structure has been modeled as a rather stiff steel box. Further discussions about the support structure is found in the earlier project [4]. The vehicle is represented by a rigid box that is allowed only to move in the forward direction. All other translational and rotational degrees for the "vehicle" are constrained.

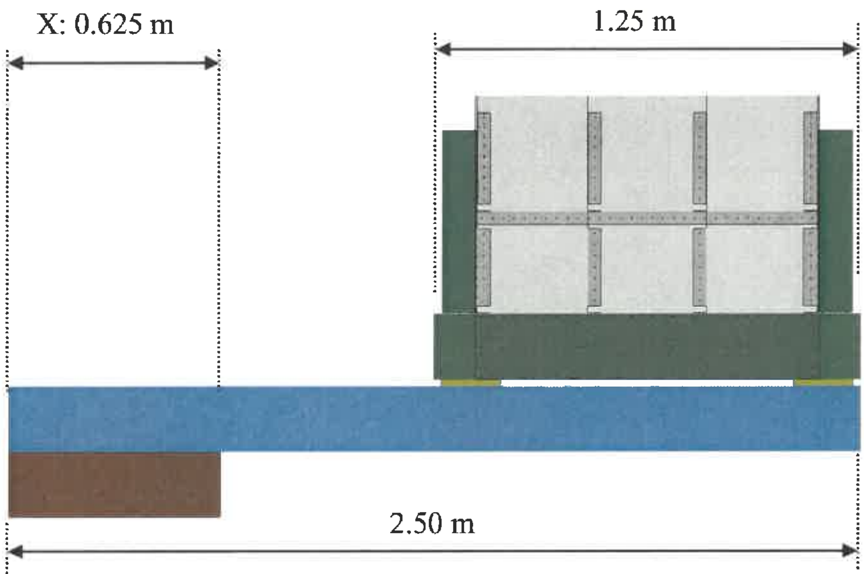


Figure 4: Top-view of the wing-profile simulation model.

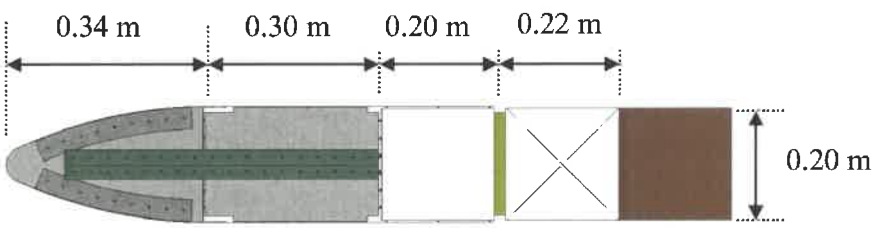


Figure 5: Side-view of the wing-profile simulation model.

Table 2 shows material data used in the simulation model of the wing. Material failure was considered in all materials (except of course the rigid material).

Table 2: Summary of component materials in the wing-profile model

Component	Material	Yield strength [MPa]	Tensile strength [MPa]
Aluminium parts	Al 2024 T3 [7]	345	570 (EPS 17%)
Steel parts	Domex 240 [8]	240	525 (EPS 25%)
Rigid parts	Rigid	-	-
Rivets	Al 2017 [9]	393	423* (EPS 30%)

EPS: True effective plastic failure strain. *423 MPa tensile strength corresponds approximately to a shear strength of 33 000 pounds per square inch (within 10%).

Reasonable strength data has been used for the rivets based on information from Normeka, see Appendix D.

4 Test set up and frangibility evaluation

The frangibility evaluation is performed according to the Aerodrome Design Manual [1]: The construction is considered frangible if the load on a wing impacting the construction is less than 45 kN and the energy onto the wing is less than 55 kJ. The energy is evaluated as the integral of the force over the travel distance of the wing profile throughout the impact, see [1].

The impact point is, in the simulations presented in this report, one meter below the mast top, see Figure 6. The velocity of the impacting wing profile is 140 km/h.

According to the Aerodrome Design Manual [1], it is recommended to use a “rigid” wing for the evaluation of frangibility of approach lightning towers and similar structures. However, in the simulations presented in this report, a “deformable” wing has been used.

The model of the wing that impacts the construction is based on the “NLR-Wing Impact Specimen” [5] which, in short, can be described as a rivet joined aluminum box structure mounted on steel supports. The wing profile has a total mass of 3000 kg. See section 3 for a detailed description of the wing-profile model.

5 Finite element model of the frangibility test set up

The frangibility model consists of the Normeka AmpliSafe Single Triangle mast model and the wing-profile model, see Figure 6 and Figure 7.

The impact point is 1.9 m above ground for the 2.9 m model and 3.9 m above ground for the 4.9 m model, and centered with respect to the front wing profile. The impact velocity is 140 km/h, which is applied as an initial velocity of the wing-profile model.

In the model, material failure of the mast is not considered, which is a conservative assumption as it leads to higher force level and energy absorption. That includes the bolts. The intended failure mode of the mast is, in the simulations presented in this report, consequently bending.

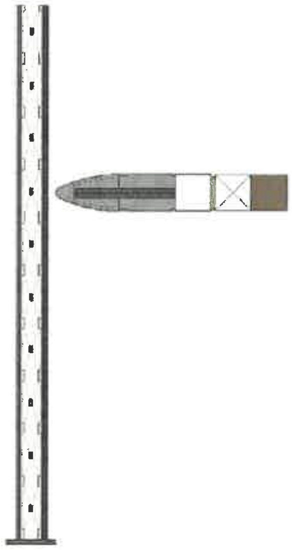


Figure 6: The frangibility model for the 2.9 m mast model.

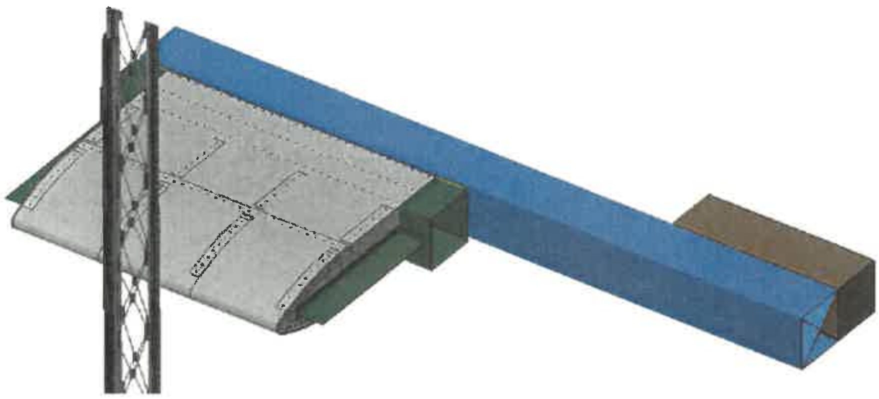


Figure 7: A close-up view of the top section where the impact occurs.

6 Results

The simulations were carried out using LS-DYNA [10]. LS-PrePost4.1 [11] was used to pre- and post-process the results. A sample rate of 100 kHz has been used to record forces.

Since peak force is an important evaluation criterion, the choice of filter is of significance. The standard does not instruct how to filter the results. It was decided to report the simulation force results after filtering it with a second order low-pass filter with a cut off frequency of 2000 Hz. Forces have been measured in two ways, i.e. where the wing is mounted to the support (similar to how it probably is measured in a physical test) as well as in the contact between wing-profile and mast. The two measuring points will, from now on, be labelled "load cell" and "contact", respectively. The force given in Table 3 is the force component in the "forward" direction, i.e. in the direction of the initial impact velocity.

The energy given in Table 3 was calculated from the contact force. If, instead, the energy had been calculated from the load cell force the difference would be less than ± 5%.

According to the calculations, as shown in Table 3, the mast does comply with the energy criterion with an upper limit of 55 kJ. The force criteria of 45 kN is also fulfilled, although the value for the 2.9 m mast model, 41.9 kN, is close to the acceptable limit.

Force verses time curves can be found in Appendix A and figures from the simulations can be found in Appendix B.

Table 3: Summary of results

Mast height [m]	Peak force (kN) filter BW 2000Hz		Energy (kJ)	No. of failed rivets
	load cell	contact		
2.9	37.1	41.9	33.6	111 of 612
4.9	35.1	35.1	32.6	172 of 612

7 Conclusions

The frangibility test has two acceptance criteria: The peak force level shall be below 45 kN and the absorbed energy shall be less than 55 kJ.

The results of the calculations are that both the energy criterion and the "peak force"-criterion are fulfilled for both mast heights.

7.1 Validity of the results

The standard, i.e. the Aerodrome Design Manual [1] does not specify a required wing impact specimen. In the present work a deformable wing specimen modeled after an actual airplane is used that is securely fastened using a steel structure into a stiff vehicle, such as a small truck, that is used for impacting the mast.

The force levels and absorbed energy depends not only on the mast but also on the stiffness of the wing impact specimen, and the test configuration: e.g. impact velocity, impact point as well as how and with which measurement system the force and energy is measured.

Other uncertainties of the wing impact specimen, e.g. material failure, could affect the results as well as the above mentioned factors. From these uncertainties follows that there is a risk that the results from a physical test will differ from the calculated results presented in this work.

[1] Aerodrome Design Manual, Part 6, First edition – 2006, ICAO, 2006.
[2] Normeka AmpliSafe Single Triangle mast drawing, drawing in STEP-format labelled "AmpliSafe single mast.STEP" supplied by Normeka AS, 2014.
[3] Test report labelled "SKMBT_C224e14100309550.pdf", supplied by Normeka AS, 2014.
[4] K. Engstrand, A. Bernhardsson, "Frangibility study of the Normeka AmpliSafe 4S-Mast", doc. no. 120071, DynaMore Nordic AB, Linköping, 2012.
[5] NLR-Wing Impact Specimen, drawing in PDF-format labelled "drawings-BeechQueenAir-wing" supplied by Normeka AS, 2012.
[6] Material data for Aluminum 6063 T6, material data sheet on pdf-format labelled "SKMBT_C20312022216100" supplied by Normeka AS, 2012.
[7] Material data for aluminum 2024 T3, material data published on url http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA2024T3, The url was supplied by Normeka AS by E-mail communication, 2012.
[8] Domex 240 YP, material data from SSAB Tunnplåt that was used for (not specified) general steel in the wing-model.
[9] Material data for rivets, material data supplied by Normeka AS by E-mail communication, 2012.
[10] Hallquist, J. LS-DYNA Keyword User's manual, version 971, Livermore Software Technology Corporation, Livermore 2007.
[11] LS-DYNA Pre- and Postprocessor LS-PrePost4.1 Manual available online at http://www.lstc.com/lspp, Livermore Software Technology Corporation, Livermore, 2014.

8 Revision record

Rev. no	Release date	Author	Description
1	2014-10-16	Anders Bernhardsson	First version.
2	2014-10-21	Anders Bernhardsson	The name of the mast, 3S-mast, is changed to Single Triangle Mast. Updated text in Section 4.
3	2015-03-20	Anders Bernhardsson	Updated text in Section 7.

9 Appendix A: Force verses time curves

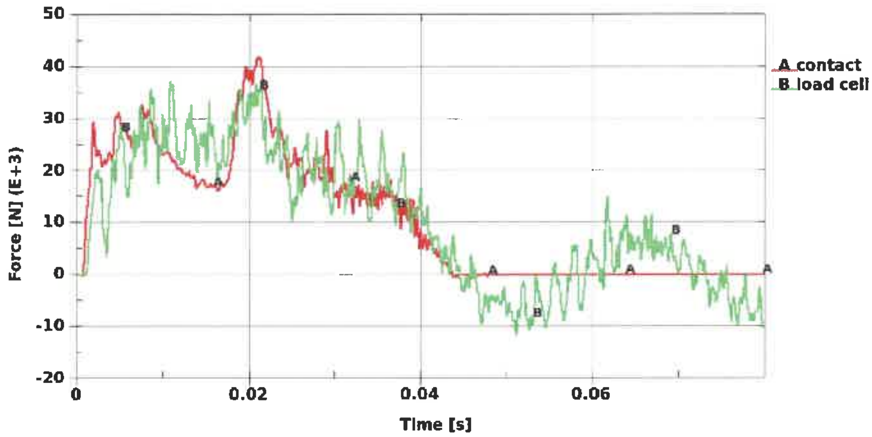


Figure 8: 2.9 m mast model.

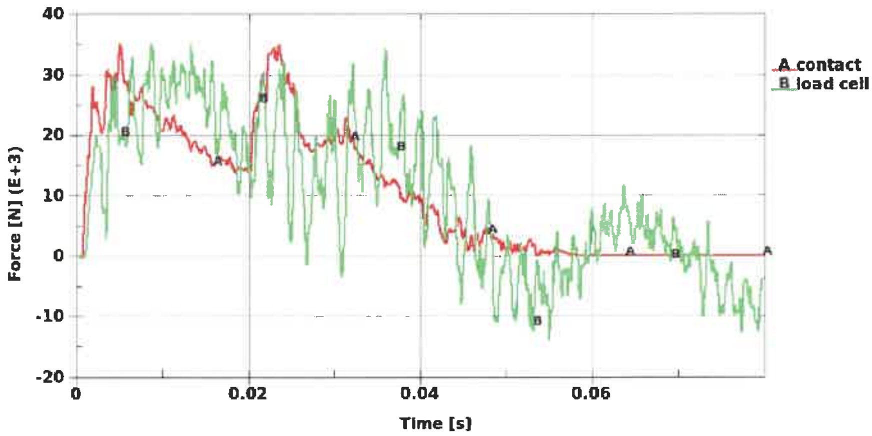
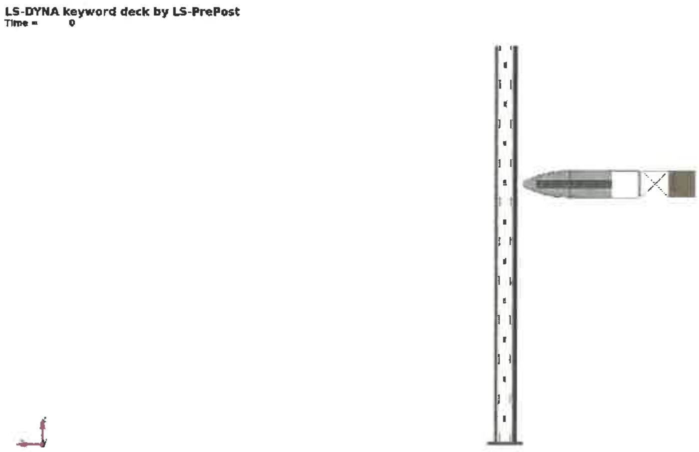


Figure 9: 4.9 m mast model.

10 Appendix B: Figures from the simulations



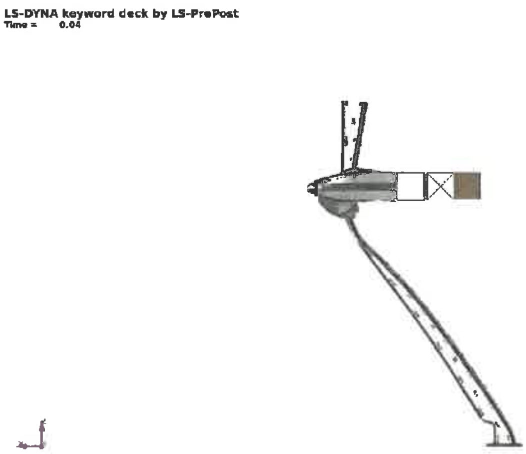


Figure 10: 2.9 m mast model at 0 ms, 40 ms and 80 ms.

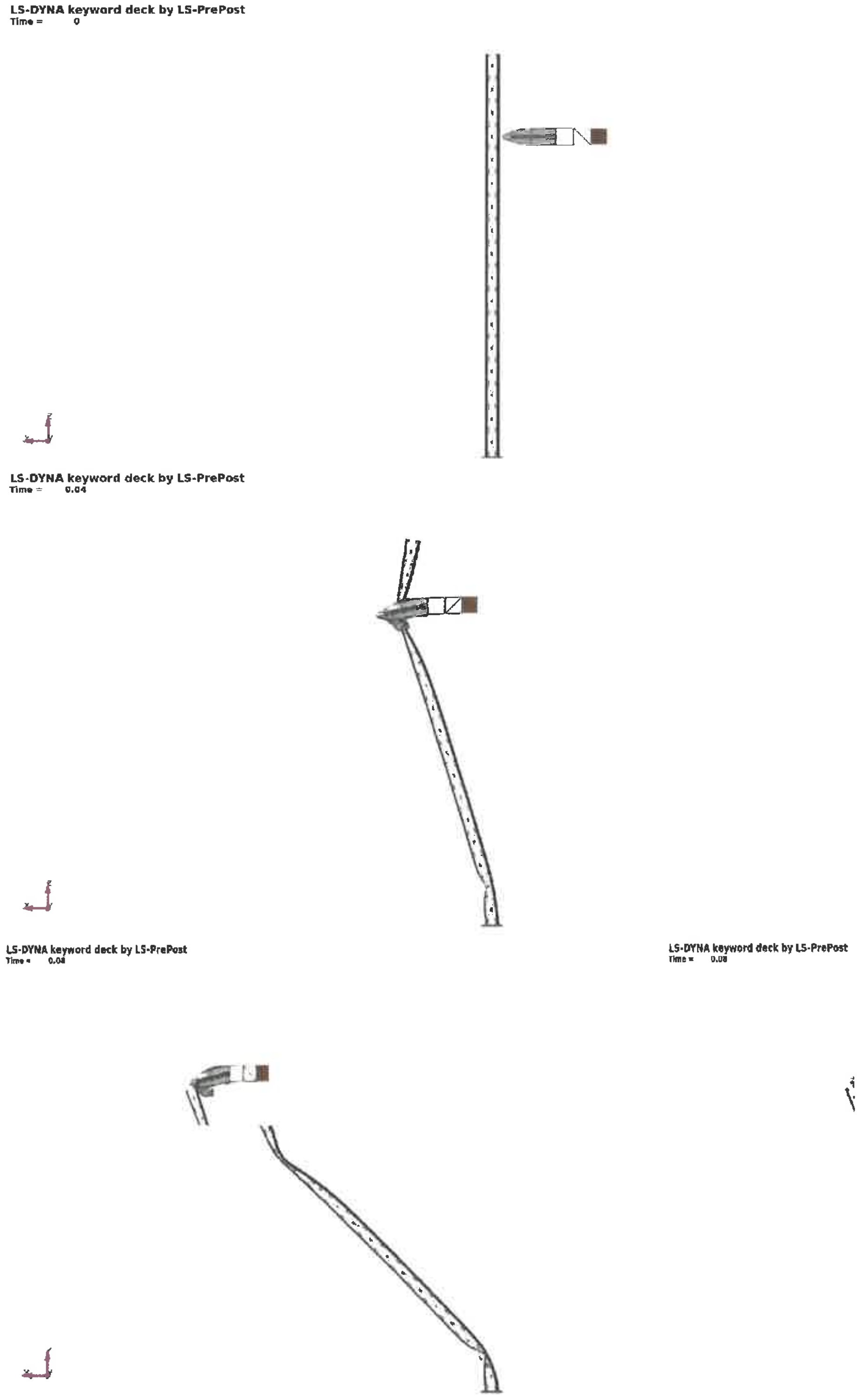


Figure 11: 4.9 m mast model at 0 ms, 40 ms and 80 ms.

11 Appendix C: Strength of corner clamping points

In the test report [3], a sliding test is performed on a mast corner section. The result from this test is the sliding distance between the corner components as a function of the force. The test setup is not described in the report so the simulation setup of the test is only an assumption.

The length of the corner section is approximately 430 mm. The clamping points are modelled as spot welds. A prescribed vertical displacement is applied to one side of the corner, while the other sided is fixed in all directions, see Figure 12.

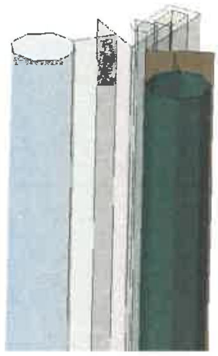



Figure 12: To the left, highlighted parts with an applied prescribed vertical displacement. To the right, highlighted parts that are fixed in all directions.

The test report [3] presents results from two tests. The simulation results will be compared with the results from Test 1 which has the highest sliding forces. The displacement is measured as the vertical displacement at the top of the corner section. The material parameters in the spot welds are varied until satisfying behavior is obtained. The chosen material parameters in the spot welds are presented in Table 4.

Table 4: Material parameters in the spot welds representing the clamping points.

Young´s modulus [MPa]	Yield strength [MPa]	Tangent modulus [MPa]
70000	265	350

The simulation results compared with the test results are presented in Table 5.

Table 5: Comparison of simulation and test results.

Displacement [mm]	Force [kN]	
	Test	Simulation
Sliding initiates	13.8	15*
0.5	30	33
1.5	58.2	46

*The spot welds in the simulations starts to yield.

12 Appendix D: Rivet strength properties

5320-00-117-5857 (MS20470D6-10, AN470D6-10, BACR15BB6D10, 001175857) Characteristics Data

MRC	Criteria	Characteristic
MATT	MATERIAL	ALUMINUM ALLOY 2017 OVERALL
MDCL	MATERIAL DOCUMENT AND CLASSIFICATION	QQ-A-430 FED SPEC SINGLE MATERIAL RESPONSE OVERALL
SFTT	SURFACE TREATMENT	ANODIZE OR OXIDE FILM OVERALL
STDC	SURFACE TREATMENT DOCUMENT AND CLASSIFICATION	MIL-A-8625 MIL SPEC 1ST TREATMENT RESPONSE OR MIL-C-5541 MIL SPEC 2ND TREATMENT RESPONSE OVERALL
CQSX	SHEAR STRENGTH	33000 SINGLE POUNDS PER SQUARE INCH
AASK	HEAD STYLE	C28 UNIVERSAL
AASU	HEAD HEIGHT	0.080 INCHES MINIMUM AND 0.090 INCHES MAXIMUM
AAZG	HEAD MAJOR DIAMETER	0.356 INCHES MINIMUM AND 0.394 INCHES MAXIMUM
AAZF	SHANK STYLE	D9 STRAIGHT
AASB	FASTENER LENGTH	0.615 INCHES MINIMUM AND 0.635 INCHES MAXIMUM
AAZE	SHANK DIAMETER	0.186 INCHES MINIMUM AND 0.191 INCHES MAXIMUM
ANEE	GRIP LENGTH	0.334 INCHES MINIMUM AND 0.354 INCHES MAXIMUM