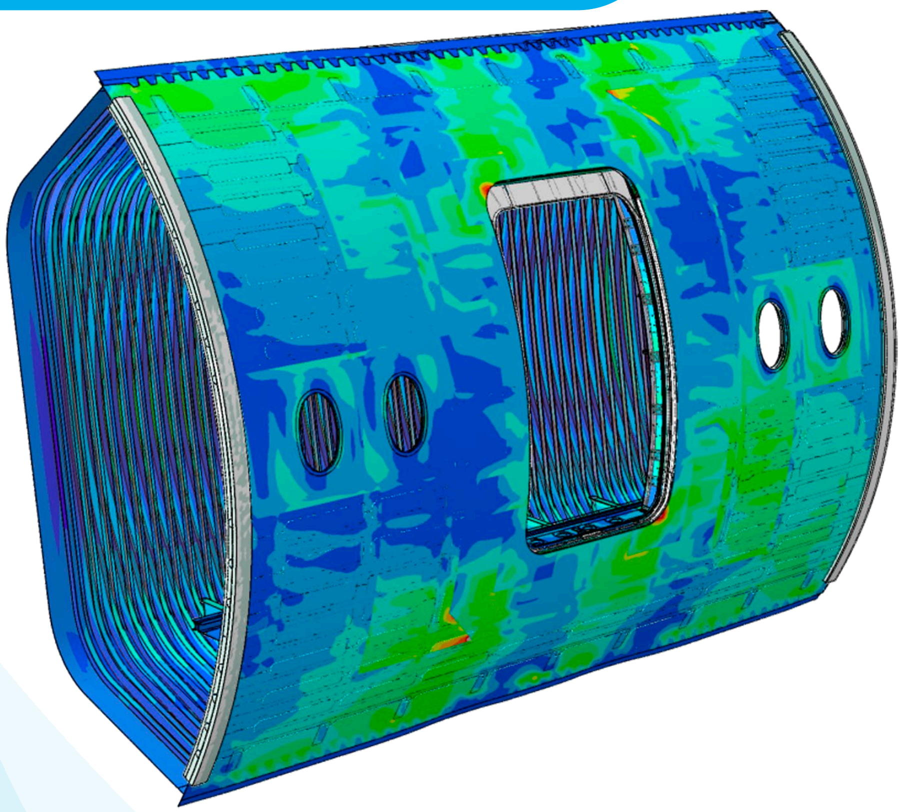
Dedicated to innovation in aerospace

NLR-TR-2017-369 | November 2017

Virtual testing, strain correlation for loads optimization of composite fuselage structure

Load identification studies

CUSTOMER: Netherlands Aerospace Centre



NLR – Netherlands Aerospace Centre

Netherlands Aerospace Centre

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EXECUTIVE SUMMARY

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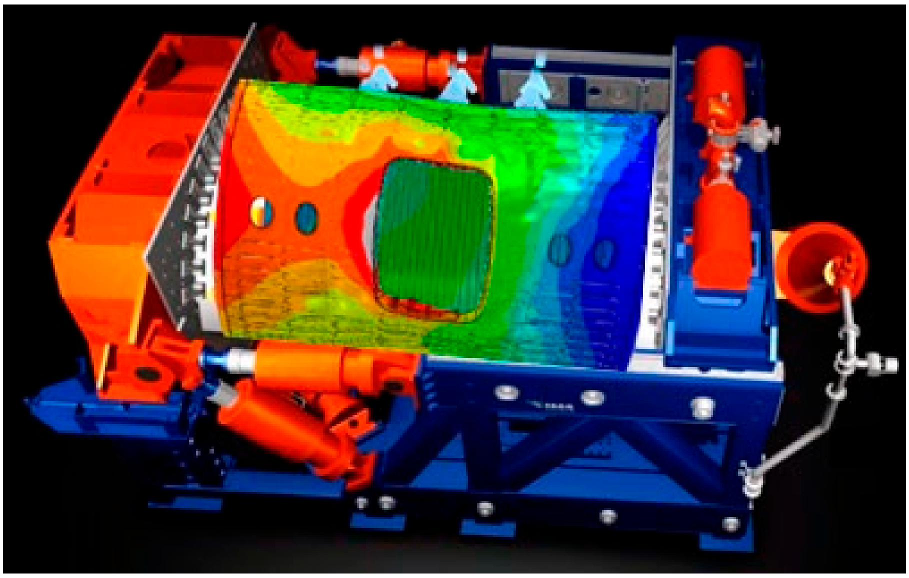

Illustration of virtual testing in a full-scale panel test rig of IMA [8]

Problem area

Innovations in full scale testing of composite fuselage structures deal among others with the reduction of time and costs needed for full-scale structural validation, which is usually done on fuselage barrel level. The aim is to achieve validation testing on a lower level of the test pyramid, in particular on large fuselage panels that do include the critical and complex structural features of the aircraft fuselage.

Description of work

Highly advanced test rigs have been developed for such panel tests and highly detailed finite element models (DFEMs) of the considered structure are needed to determine the correct loading for such tests. The test rigs make use of many fixations and actuation systems (up to 50 or even more) and large numbers

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DESCRIPTOR(S)
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strain gauges
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Abaqus

(hundreds) of sensing signals. This study investigates the efficient load determination procedures for complex and full scale tests of large composite fuselage panels using virtual testing methods and FE models, with a focus on the strain correlation and loads identification method, the development of the efficient virtual testing modelling and analysis process and the enhancement of accurate strain extraction methods and element selection.

Results and conclusions

This report presents some results from investigations on efficient load determination procedures for complex and full scale tests of large composite fuselage panels using virtual testing methods and DFEMs. Small and large models (panel DFEMs in Abaqus) and several tools for strain extraction and optimisation have been used. Adequate loads identification results were obtained.

Applicability

The procedure used in this study is also applicable to metallic fuselage panels, as well as to other heavily loaded structures like aircraft wings.

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Summary

In this study load identification methods will be investigated on two different finite element models, with the goal to enhance and understand a load determination procedure for a complex and full scale virtual test of large composited fuselage panels. With proper load identification methods full scale tests of a complete fuselage barrel can be simplified to a large fuselage panel tests. This will have major time and cost benefits in the validation of fuselage structures.

The focus of the investigations was on the strain correlation of the end result and the load identification method, the development of the efficient virtual testing modelling and analysis process and the enhancement of accurate strain extraction methods and element selection. The goal of the study was to perform a correct load identification on the DFEM.

The method used for the load identification is based on a linear least squares procedure that determines the linear combination of load factors that yields the best approximation of a set of reference strains from the barrel test. Before the analyses are carried out and the results are presented, first the two finite element models are presented. Then the method is further explained and also the error calculation which are the root means square of the relative error and the relative root mean square of the error.

One of the two finite element models represents a simplified aluminium panel (SFEM), the other is a detailed model of the fuselage panel (DFEM). The SFEM is used for the quick calculation and to create understanding of the method. This is done by carrying out linear analyses and then nonlinear analyses. Then changes are made to the number of loads used in the analysis. With the aspects found in the results of SFEM, the choices are made for the linear and nonlinear analyses of the DFEM. The different aspects of the analyses that have an effect on the result of the load identification are the neglecting of lower strain values, the increase in loads on a model introduces more insecurity, the influence to the choice of the sensor position and number of sensor elements. These aspects are found back in the DFEM analyses. Potentially there are also numerical issues like the singularity of the unit load matrix.

The load identification of the linearly analysed FE models can be performed with excellent results. For the nonlinear analyses of SFEM also yield good results, but for the nonlinear analyses of the DFEM an accurate reproduction of the strain field was not possible, at this moment. Aspects as sensor position and choice of magnitude of forces play an important role in the quality of the results.

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Contents

Abbreviations

ACRONYM	DESCRIPTION
NLR	Netherlands Aerospace Centre
LC	Load case
LU	Unit load
CM	Control model
RMSE	Root mean square error
RMSRE	Root mean square relative error
RRMSE	Relative root mean square error
FE	Finite element
FEM	Finite element model
DFEM	Detailed FE model
SFEM	Simplified FE model
ε	Strain
α	Load factors
CAD	Computer added design
PAX	Passengers
dof	Degrees of freedom
lin	Linear
nonlin	Nonlinear
pert	Pertubation step

1 Introduction

With the strong growth of global air traffic, approximately doubling every 15 years, a global demand of about 35000 new large passenger and freighters aircraft between 2017 and 2036 [1] is expected. To accommodate this strong growth, Airbus as a global leader in designing, manufacturing and delivering aerospace products, has to operate at the forefront of the aviation industry by building innovative commercial aircraft [2]. Among the many innovations considered in new aircraft is the use of new structures and materials. In particular, lightweight carbon composite structures are introduced in higher proportions and more areas of the aircraft, like in wing and fuselage structures. For example the research project MAAXIMUS [4] was aimed at achieving the fast development and right-first time validation of a highly-optimised composite fuselage thanks to a coordinated effort between virtual structures development and composite technology.

Fuselage structures of most aircraft are subjected to the combined loading of cabin pressure and fuselage bending. It is therefore highly desirable that these new constructed structures or materials are tested under those complex loading conditions in full-scale. Full-scale aircraft fuselages validation is carried out to critical and complex structural features such as circumferential or longitudinal joints, PAX door and the corresponding door surround structure or representative floor structures [3]. These tests are currently done at barrel level and are very expensive and time consuming. Reducing these test form barrel level to panel level would mean significant benefits in time and cost consumption in future research, see figure 1.

Extensive virtual testing on finite element (FE) models can be done to capture the behaviour of full-scale tests [5], for example of barrel in a full-scale panel test so the panel test is fully consistent with the full-scale barrel level test. In

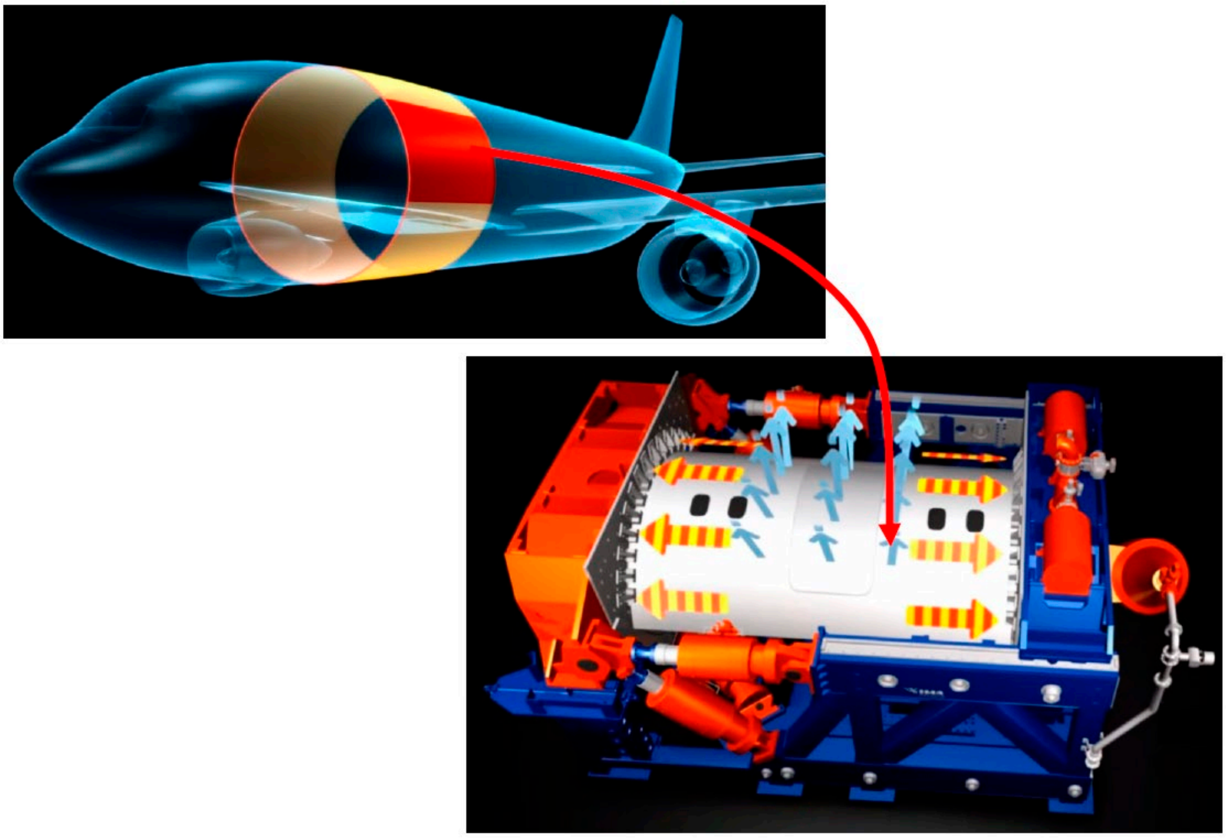

Figure 1: Scale reduction visualization of the full scale test [8]

previous studies at NLR [3], a complete model of an aircraft fuselage door surround panel was built, here further referred to as the detailed FE model (DFEM). Though saving time, testing a fuselage panel rather than a full size fuselage barrel also bring some challenges. Pressures and forces used in barrel test that represent the in-flight strain field in the fuselage cannot be scaled directly to panel level, because of the loss of stiffness form the circular structure. In the paper of Vankan, van der Brink and Maas [3] a basic method for the load identification and strains evaluation is presented and a virtual correlation analysis was done for the load identification of the detail DFEM. The load identification is a method of determining the forces that needs to be implemented in the panel level test rig to simulate the strain field of a given reference strain field. In the previous research the virtual tested load identification the correlation between the panel strain field and the reference strain field was not very high, with the conclusion that further investigation is necessary, especially in the element selection of the load identification.

This study investigates the efficient load determination procedures for complex and full scale tests of large composite fuselage panels using virtual testing methods and FE models, with a focus on the strain correlation and loads identification method, the development of the efficient virtual testing modelling and analysis process and the enhancement of accurate strain extraction methods and element selection.

A specific goal of the study is to perform a reliable load identification on the DFEM. To reach this goal we aim to get full understanding over the load identification and the results, so in this research of the load identification there is looked at different aspects: the linear as well as the nonlinear analyses, the influence of the unit loads (LU) and force magnitudes and the sensors elements and sensor element positions.

Outside of the scope will be the loads location for the load identification as they are pre-set in the model.

Because of the model complexity of the DFEM, a simple aluminium panel will be investigated first to gain a better understanding about the effect of the loads identification. This FE model is an in-house build panel of NLR and is named accordingly as simplified finite element model (SFEM). The SFEM makes it quick in calculating results and easier for interpretation of these results. Both the FE models are outlined in the next chapter (chapter 2). In chapter 3 the load identification method and post-processing methods used in this report are clarified, further the procedures and case that are that are attended to and the software that is used. Chapter 4 presents and discusses the result of the load identification on the SFEM procedures described in the method. This ends with a conclusion on the different aspects of the load identifications and the recommendations for the DFEM load identification. In chapter 5 the results and discussion of the DFEM's load identifications are given. Chapter 6 will hold the conclusion for this research and the recommendations for follow on studies.

2 Considered FE models

This chapter presented the two FE models (SFEM and DFEM) used for testing the load identification. It covers the composition, material, load placement and the element choice of the models.

2.1 Simplified finite element model (SFEM)

The SFEM is an in-house build panel of NLR and it is used because it is small and can be used for quick calculation time. The panel is 577mm by 1450mm and build-up from four Frame Beams, four Stiffener Beams and a Skin, given in figure 3. The Frame Beams are vertical Z-beams and Stiffer Beams are the horizontal Z-Beams, with both the structures respectively presented in figure 2. Over the beams the aluminium Skin is spanned. The beams are made of Aluminium 7075 while the Skin is Aluminium 2024, all with a poison ratio of 0.3. When looking form the inside as figure 3 the right side of the panel will be clamped in. All the other sides have boundary conditions on the edge so they cannot rotate and move in the x direction (see axes lower left corner of figure 3). The forces on the panel are: on the top and bottom side the same shear forces (Shear TB), on the left side a shear force (Shear L) and on the left side a compression force (Compression). The magnitude of the forces will differ throughout this paper. The elements used as sensor elements for the load identification are elements on Skin. These sensor elements are randomly or specifically chosen, depending on the parameters of that study. Within an element the direction of the strain can also vary in direction E11, E12 and E22. The strains in the different direction will be presented in single precision, this means that the strains have eight significant digits.

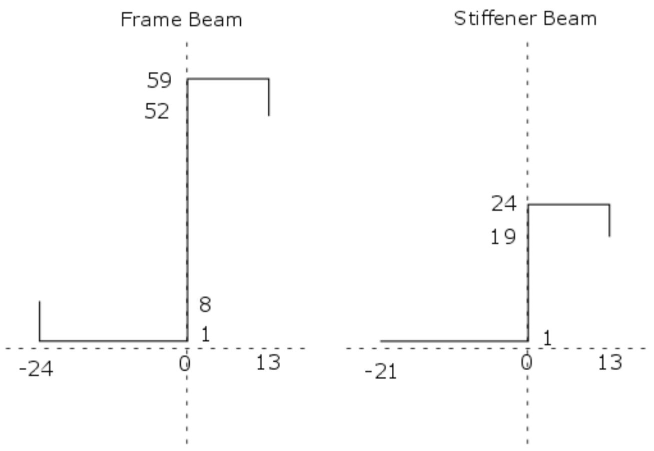

Figure 2: Frame beam and stiffener beam structure

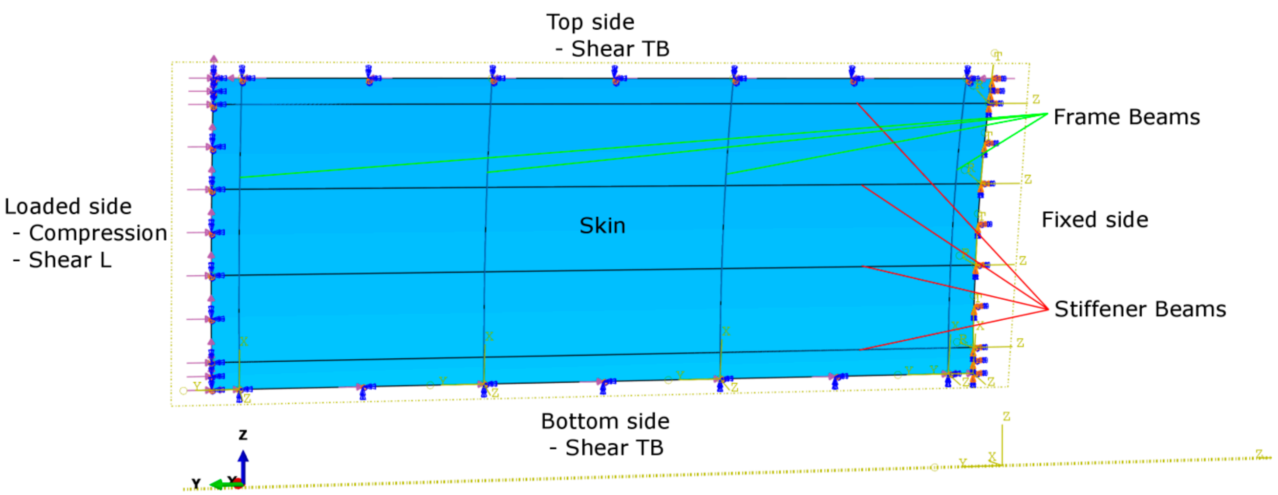

Figure 3: SFEM

2.2 Detailed finite element model (DFEM)

The DFEM is also a NLR built panel [3], which is realistic model of an aircraft fuselage panel. It exists out of highly complex structural features of PAX door and the corresponding door surround structure as well as representative floor structures. The original CAD model of the panel exists of an approximate of 1000 different parts, see figure 4. In the DFEM the number of parts is brought back to about 250 parts in which some structures are replaced by constrains, for example the PAX door and windows, as they do not contribute to the in-plane stiffness of the panel. This results in a mesh model of about 1100k elements, 1.1M nodes and a FE problem with the size of approximately 4.6M dof's.

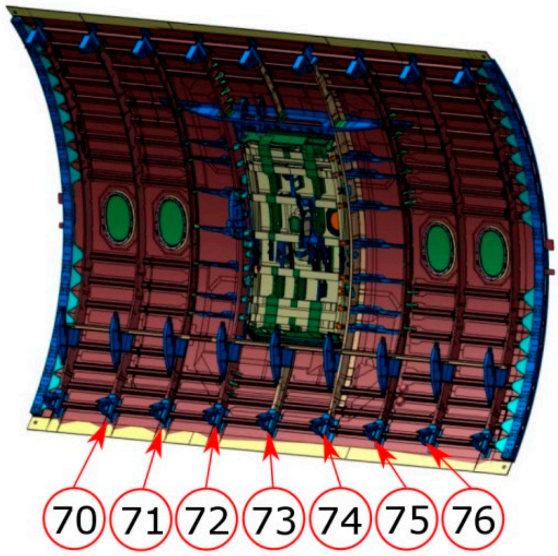

Figure 4: CAD model of fuselage side panel [3]

The panel size is from top to bottom 4091mm and from left to right 5700mm. The parts are all kinds of different materials: carbon composites, aluminium, steel, glass-fibre composites and titanium. Next to different materials between parts the composite parts vary significantly in the thickness and lay-up, the thickness ranges 3mm in the more peripheral skin regions up to about 12mm near the PAX door. Some lay-up consisted of nearly 100 plies. Conclusion is that it is highly complex.The load and boundaries conditions of DFEM are given in figure 5 and here further explained. The left side of the DFEM is fixed edge, so is clamped in every direction. On the other side 3 nodal forces and 3 moments are introduced, which are the main bending forces of the panel. Most of the other loads are the representation of a constrained in the fuselage barrel. Frame spreaders are 7 individual moments that are loaded on both sides of the frame. Skin spreaders are 42 forces that are all the same and are seen as one independent unit load. The X-Beam forces and moment are divided as 4 forces and 4 moments. In total 23 forces are presented in figure 5. Only 22 will be looked at as the internal pressure is left outside de scope. In figure 4 the numbers 70 till 76 given, they corrensponed with a location on the vertical axis on the DFEM. So Frame spreader 72 is location on the

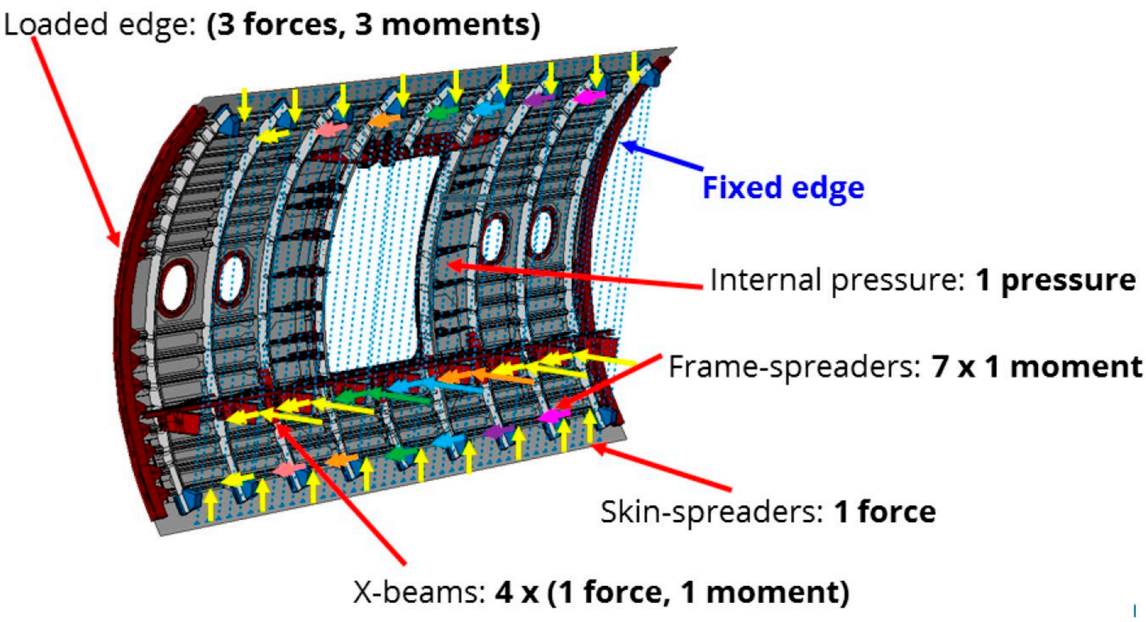

Figure 5: DFEM [3]

same vertical axis as cross beam force 72. As the DFEM is a virtual representation of a real fuselage panel. The location the sensor element is also limited to about 700 different elements that hold the position of strain gauges in the real test. For the extraction of the strains a python file was used of the NLR. For the load identification of the DFEM different selection of these strains will be used. The information of the strains will be read out in double precision, this mean that the strains will have sixteen significant digits.

3 Methods

In this chapter the methods that are used throughout the report for the load identification and post-processing are explained. Further information is given about the software, the procedures and the condition number.

3.1 Load identification

The load identification is a least square method for determining the magnitude of loads that need to be implemented on a panel to simulate a given reference strain field. This method uses the known strain fields (the reference strain field and the unit load (LU) strain fields) to calculate load factors (α). When multiplying the load of the LU's with the load factors the forces that need to be implemented are calculated.
The goal is to recreate a reference strain field that comes as input data, in this study the reference strain field is simulated by loading a FE model with a curtain number of loads and a curtain magnitude, which are known. The case of creating the reference strain field with curtain loads and magnitudes will be further referred to as the 'load case' (LC). From the complete strain field of the LC a certain amount of sensor elements are being picked out. These will be used for the load identification. Next the unit-loads (LU) strain field are to be found. This is done by running the model individually for each of the forces, so for every LU there is a stain field created. In paragraph 3.1.1 is described how to gain the strain field information out of Abaqus.
From all known strain fields certain strain elements are chosen (sensor elements). The sensors strain elements of the LC will form a vector: ε^b. The unit load strains are some chosen strain sensor elements and collecting them in a matrix: ε^p, which gives the unit load matrix. The vector ε^b and the matrix ε^p are build-up as follows:

$$\boldsymbol{\varepsilon^p} = \begin{bmatrix} {\varepsilon_{11}}^{1,1} & {\varepsilon_{11}}^{1,2} & \cdots & {\varepsilon_{11}}^{1,23} \\ \vdots & \vdots & & \vdots \\ {\varepsilon_{11}}^{n,1} & {\varepsilon_{11}}^{n,2} & \cdots & {\varepsilon_{11}}^{n,23} \\ {\varepsilon_{12}}^{1,1} & {\varepsilon_{12}}^{1,2} & \cdots & {\varepsilon_{12}}^{1,23} \\ \vdots & \vdots & & \vdots \\ {\varepsilon_{12}}^{n,1} & {\varepsilon_{12}}^{n,2} & \cdots & {\varepsilon_{12}}^{n23} \\ {\varepsilon_{22}}^{1,1} & {\varepsilon_{22}}^{1,2} & \cdots & {\varepsilon_{22}}^{1,23} \\ \vdots & \vdots & & \vdots \\ {\varepsilon_{22}}^{n,1} & {\varepsilon_{22}}^{n,2} & \cdots & {\varepsilon_{22}}^{n,23} \end{bmatrix} \qquad \boldsymbol{\varepsilon^b} = \begin{bmatrix} {\varepsilon_{11}}^{1,barrel} \\ \vdots \\ {\varepsilon_{11}}^{n,barrel} \\ {\varepsilon_{12}}^{1,barrel} \\ \vdots \\ {\varepsilon_{12}}^{n,barrel} \\ {\varepsilon_{22}}^{1,barrel} \\ \vdots \\ {\varepsilon_{22}}^{n,barrel} \end{bmatrix}$$

Figure 6: Composition of vector ε^b and the matrix ε^p

Were n being the number of sensor elements and the numbers 1 till 23 the amount of LU's (in this case 23 different LU's). From this data the load identification can be performed with the equation described in paper of W.J. Vankan, W.M. van den Brink and R. Maas [3]. The equation is a least squares procedure that determines the linear combination of these columns and results in a set of load factors**,** which yields the best approximation of the reference strains.

$$\min{}_{\alpha}|\varepsilon^b - \varepsilon^p\alpha|^2 \rightarrow \alpha = \left({\varepsilon^p}^T \varepsilon^p\right)^{-1} {\varepsilon^p}^T \varepsilon^b \qquad (1)$$

In this equation ε^b is a vector with the known strain data in sensor points, ε^p is a matrix of the UL strain data in the sensor points, which results in the load factors, α. This load factor is the ratio between the magnitudes of the load

used in the LU and the magnitude of load that should be used to create the LC. This means there are as many load factors as there are LU's.
Calculating the magnitude of the loads for the input of the 'Control model' (CM) is thus simply α times the forces of the UL. The strain field of the CM is determined and compared with the LC in the post-process.

3.1.1 Software

In this paragraph is described how the strain fields of LC, LU, and the CM are gathered for both FEM. For both FEM applies that they are built in Abaqus. Python is supporting Abaqus with scripts which makes it straightforward to change loads and reading out the final strain results. The strain field results of the chosen sensor elements are uploaded to Excel files. For the load identification of the SFEM Python is applied, but for the DFEM the load identification runs in Matlab, which is mainly for convenience. With the information of the load factors, the load for the CM model is calculated, with this another Abaqus model for the CM strain field is ran. Matlab is furthermore used for post-processing the results of the two models into figures and the calculations of the error. Considering linear and nonlinear analyses in Abaqus multiple options arise, for example a nonlinear LC strain field is to be reproduced with a linear LU's case. This is introduced in the Abaqus software as 'steps'. In the next section the different options that are used in Abaqus are discussed and why they are functional.

3.2 Procedures and cases

For the analyses of the LC, LU's and CM different step options of Abaqus are used. The various steps that are used in this paper are: Static Linear Perturbation step (pert), General Static Linear step (lin) and the General Static Nonlinear step (nonlin).
A combination of the step for the load case, the step for the unit loads and the step for the control is from now on referred as a procedure. All different procedures handled in the study, with their designated number, are given in table 2. As the SFEM is quick in calculating all the different options of the procedures are being evaluated. Starting with an all linear analyses of Abaqus and comparing them. Afterward the different options are used to solve the nonlinear LC and the possibilities of recreating those with linear and nonlinear LU and CM. The conclusion of the SFEM analysis is that the interesting procedures for the DFEM are procedure 1 and 4, but procedure 2 is also evaluated because of the advantages if it could be functional.
The word 'case' is used to indicate a load identification given a procedure. The variables in a case can be the number of loads in LC, the amount of LU, the amount of sensor elements and sensor element locations for the load identification.

Table 2: Procedures

Procedure	Load Case (LC)	Unit Loads (LU)	Control model (CM)
0	Static, Linear Perturbation	Static, Linear Perturbation	Static, Linear Perturbation
1	General, Static Linear	Static, Linear Perturbation	Static, Linear Perturbation
2	General, Static Nonlinear	Static, Linear Perturbation	Static, Linear Perturbation
3	General, Static Nonlinear	Static, Linear Perturbation	General, Static Nonlinear
4	General, Static Nonlinear	General, Static Nonlinear	General, Static Nonlinear
5	General, Static Nonlinear	General, Static Nonlinear	Static, Linear Perturbation

3.3 Post-processing

The post processing of the information from the load case and the control model is done with Matlab. There are two variables that are checked throughout the study: the load factor and the residuals. Both are explained below.

The load factor can be checked when the forces that created the LC are also known. Normally this is not the case and is this the result that should be provided by the load identification. The intended load factors are calculated by dividing the load magnitude of LC by magnitude of LU's loads.

$$\frac{F_{LC,i}}{F_{LU,i}} = \alpha_{intend}$$

With this information is checked how much the calculated load factors deviate from the intendent ratio.

$$\frac{\alpha_{intend} - \alpha_{calc}}{\alpha_{intend}} = \beta$$

The closer β is to zero, the better the resemblance between the LC load magnitude and the calculated load magnitude. If the magnitude of the LC loads can exactly be reproduced, the strain field of CM is per definition a good representation of the LC strain field. In the linear cases, it means that a high number of β results in a poor reproduction of the strains field, but in the nonlinear case this has not to be the issue.

The difference between the strain field of the LC and strain field of the CM will be called the residuals and should be as small as possible. Different statistical evaluations will be used to say something about the residuals. These are the Root Mean Squared Relative Error (RMSRE) and the Relative Root Mean Square Error (RRMSE). Both statistical evaluations originate from the Root Mean Squared Error [6].

- RMSE = $\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\varepsilon_i^{LC} - \varepsilon_i^{CM}\right)^2}$ (2)

With ε_i^{LC} is the LC strain in element i, ε_i^{CM} the CM strain in same element i and n the number of elements used. For the RMSE yield that the lower the value, the better the calculated CM in terms of its absolute deviation. Because of the quadratic behaviour of the RMSE it is sensitive for outliers. A few large errors can result in a large RMSE. If a RMSE value is low enough, is dependent on the values in the LC strains. Another way to make the comparison with the LC are the RMSRE and the RRMSE, both are relative to the LC strains.

The RMSRE is the RMS of the relative error. This result can be polluted with low strains in ε_i^{LC} as this results in high values for the RMSRE.

- RMSRE = $\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\varepsilon_i^{LC} - \varepsilon_i^{CM}}{\varepsilon_i^{LC}}\right)^2}$ (3)

With ε_i^{LC} is the LC strain in element i, ε_i^{CM} the CM strain in same element i and n the number of elements used. The results of the RMSRE are considered optimal when they are smaller than 0.01, which means the error is one percent of the LC strains. They can be considered fair if the value is <0.1 and bad if they are >0.1.

The RRMSE uses the RMSE and divides it by the mean of the LC strains.

- RRMSE = $\frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\varepsilon_i^{LC} - \varepsilon_i^{CM}\right)^2}}{\bar{\varepsilon}_i^{LC}} * 100\%$ (4)

With ε_i^{LC} is the LC strain in element i, ε_i^{CM} the CM strain in same element I, $\bar{\varepsilon}_i^{LC}$ is the mean of all the LC strains in i and n the number of elements used. The RRMSE give an indication of the accuracy of the reproduced model. It is excellent if the value is <10%, good if it is between 10% and the 20%, fair if it is between 20% and 30% and poor if the RRMSE >30%.

3.4 Condition number

The condition number is a value that says something about the singularity of a matrix. When solving a matrix equation in the form of $Ax = b$, the condition number of the matrix A can be used to gauge the stability of a function. A large condition number of this matrix means that small changes in x result in significant changes in b, unreliable results and the matrix A will be ill conditioned. If the condition number is significantly small it means that small changes and something bigger changes of x result in small changes in alpha and even bigger change in x result in small changes of b.
The logarithm of the condition number is an estimation of the number of significant digits that are lost in the solution. This number is the worst-case scenario for the loss of precision. So, if a condition number is called small depends on the precision of input values in relation to the logarithm of the condition number.
Roughly it means that a matrix is ill conditioned, when the logarithm of the condition number is higher than the precision of the input values.
The condition number can be calculated by dividing the largest with smallest singular values, which are results of the value decomposition of the matrix A [7].
In the load identification the equation to solve is equation 1. Rewriting this equation results in a equation of the form of:

$$E\varepsilon_b = \alpha \quad ,with \quad E = \left(\varepsilon^{p^T}\varepsilon^p\right)^{-1}\varepsilon^{p^T}$$

The condition number of matrix E can be used to give information about the robustness of the equation. It turns out that the condition number of matrix E is equal to the condition number of ε_p. This condition number will be used to check if the answers of the load factors alpha are valid. This is done by checking if there are enough significant digits in the input values of ε_p.

4 Simplified Finite Element Model (SFEM)

In this chapter the results of the load identification out on the simplified finite element model will be presented and discussed, starting with the linear procedure working our way up to the nonlinear procedures, then looking at other variables of the load identification. At the end of the chapter there is a small conclusion that is sums up the findings and makes important choices for the study on the DFEM model. The details of the SFEM are already described in chapter 2.1 of this paper. The different procedures that will be treated are clarified in chapter 3 section 3.

4.1 Linear perturbation step versus General linear step

In this section the first two procedures 0 and 1 are compared. These two deviate from each other in the LC step. Procedure 0 has a static perturbation step and procedure 1 a general linear step. Since the static perturbation step and the general linear step are both calculated with linear superposition method. The difference arises when another step follows the previous. When a perturbation step is used as first step the following step uses no information form the results of the perturbation step, so the input values of the second step are the same as those of the perturbation step. After a general linear step the next step uses the output of the general linear step as input for the next step [9]. This visualized in figure 7. Concluding the static perturbation step and the general linear step should yield the same result, as there is only one step in the SP model.

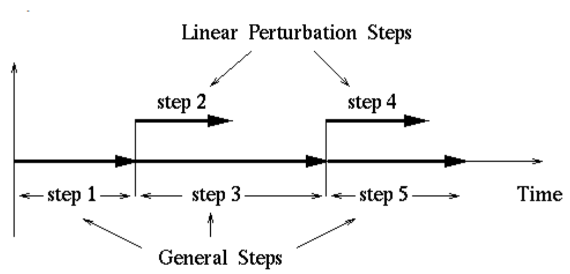

Figure 7: Linear Perturbation -versus General Step

This is simply checked by running procedure 0 and procedure 1 and comparing the strains field data of both procedures. In table 3 the strains of both the LC's can be found for the elements 350-1 and 1000-1. These yield exactly the same result, as expected. The choice was made to use the linear perturbation step for all the linear calculations in further linear calculations.

4.2 Static perturbation step (procedure 0)

The first load identification is procedure 0 which entails a linear LC, LU's and CM. The results of this load identification are presented and discussed in this section. With linear super position behaviour of the linear perturbation step, it is expected that the residuals are being zero and the load factor can be calculated exactly. There are three sensors used to solve three equations this gives three load factors, so for a linear system this would be exactly solvable. Carrying out the load identification described in chapter 3, leads to the rest of the result found in table 3. Worth noticing is that the load factors are not exactly the ratio between the LC magnitude and the LU magnitude. Consequently there is also a different in the strains between the LC and the CM. Also worth noticing is that using different element as input for the load identification, the load factors yield different results, this means that the load identification is sensor element depended. When looking at the strain residuals (difference between strains of LC and strains of CM) more closely, the RMSE residuals for case 0-1 are 2.29e-7. The average of the strains in the LC is 3.17e-3, so on average there is roughly a factor 10.000 between the residuals in the strains and the LC strains, which is again a good result. To visualize this, a correlation plot can be found in figure 8 between the strains of the LC and the strains of the CM. Because there is no

Table 3: Procedure 0 and 1, loads and strain information

Procedure-Case	0-0	1-0	0-1
LC Magnitude	[150,300,-200]	[150,300,-200]	[150,300,-200]
LU Magnitude	[100 100 100]	[100 100 100]	[100 100 100]
# Sensor Points	3	3	3
Sensor Element	350-1	350-1	1000-1
Load Factor UL1	1.49901	1.49901	1.50038
Load Factor UL2	3.00005	3.00005	2.99993
Load Factor UL3	-1.99907	-1.99907	-2.00002
Stains LC			
350-1	-1.892E-04	-1.892E-04	-1.892E-04
350-1	6.803E-04	6.803E-04	6.803E-04
350-1	-7.591E-03	-7.591E-03	-7.591E-03
1000-1	2.641E-04	2.641E-04	2.641E-04
1000-1	-9.726E-04	-9.726E-04	-9.726E-04
1000-1	-8.480E-03	-8.480E-03	-8.480E-03
Strains CM			
350-1	-1.897E-04	-1.897E-04	-1.891E-04
350-1	6.822E-04	6.822E-04	6.799E-04
350-1	-7.591E-03	-7.591E-03	-7.591E-03
1000-1	2.640E-04	2.640E-04	2.642E-04
1000-1	-9.721E-04	-9.721E-04	-9.728E-04
1000-1	-8.481E-03	-8.481E-03	-8.479E-03

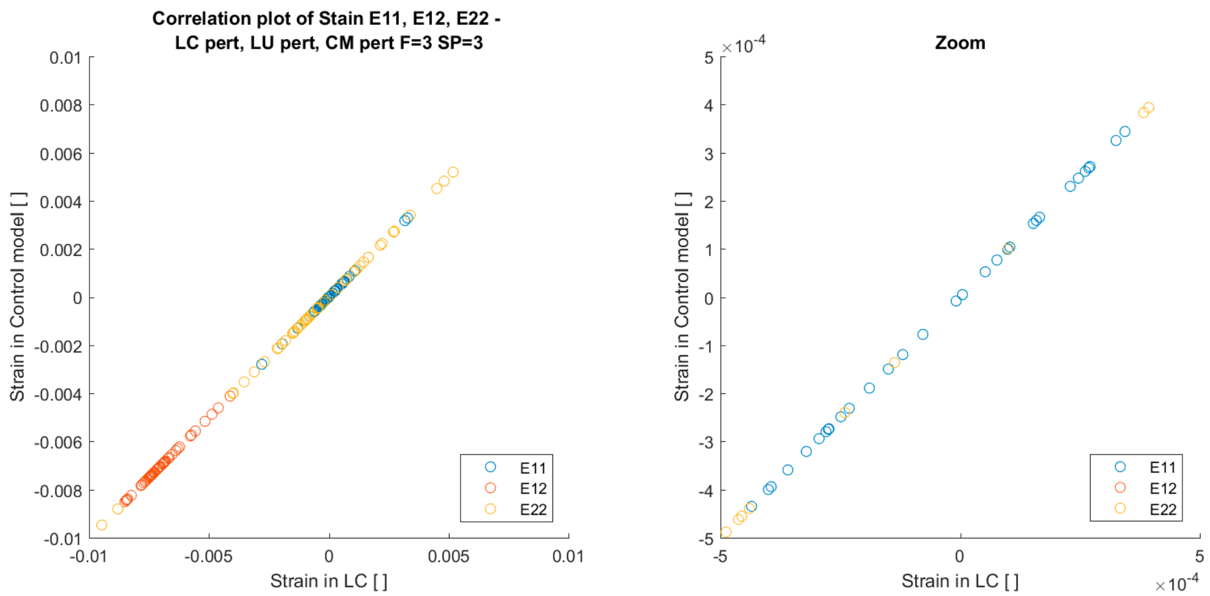

Figure 8: Correlation between the LC and CM strains

Table 4: Procedure 0 with LC and LU's magnitude [100,100,100]

Procedure 0	1076-1 [E11]	1076-1 [E12]	1076-1 [E22]
Strains - LU0	5.5979E-05	-6.5386E-04	1.7773E-04
Strains - LU1	-3.0087E-04	3.5922E-03	-2.5820E-03
Strains - LU2	-3.0001E-04	3.5998E-03	-4.4081E-04
Sum LU	-5.4491E-04	6.5382E-03	-2.8451E-03
Strains - LC	-5.4491E-04	6.5382E-03	-2.8451E-03
Error	**2.1828E-11**	**-5.8208E-11**	**-1.4552E-11**
Strains - CM	-5.5147E-04	6.6161E-03	-2.8767E-03
Residuals (LC-CM)	**6.5626E-06**	**-7.7907E-05**	**3.1667E-05**

visible deviation from the centreline, it can be said that despite of the error in the load factors the CM is pretty good representation of LC. Although this is a good result there is expected that the error goes to complete zero. With this in mind some studies are done to find out where this error is coming from.

In the first investigation the linear super position behaviour of the SP model is verified. If the SP model is linear is should yield that the strain results of UL0 + UL1 + UL2 with magnitude 100, are the same as the LC strains with magnitude [100,100,100]

$$strains\{\mathrm{UL0}(100) + \mathrm{UL1}(100) + \mathrm{UL2}(100)\} = strains\{LC(100{,}100{,}100)\}$$

The study was carried out and the strains of sensor point 1076-1 were put in table 4. As the table shows the strains are almost identical only there is an error of 1e-11. This can be explained by the way the data is obtained, the strains of Abaqus are read out as single precision values. This means that they have eight significant digits. As the first value is in the order of 1e-4 the last significant digit is in het order of 1e-11. For the model it means that an error in the order of 1e-11 is an inaccuracy of the retrieved strains. The conclusion is that every error of 1e-10 or less is per definition excellent. Also there can be concluded that the SFEM is linear and there are no nonlinear effects within the model.
Now solving the same problem with a CM, calculating the load factors for this case results in: [0.9616280, 1.00857651, 1.00610995], which is pretty bad. The residuals of element 1076-1 are consequently not very good, which can also be found in table 4 and are in the order of 1e-5. Somehow in calculation of the load factors a big error is introduced.
To check if the error in the load factors is due to the small differences between load case strain and the unit loads strain, the difference between the LU's strains and the LC strains is made twice as big and then the load identification redone. This results in the load factors of: [0.96162808, 1.00857651, 1.00610995], which is pretty must the same answer.
Concluding the LU's are a good representation of the LC, and somewhere in the calculation of alpha an error is introduced.

So secondly the calculation of the load factors is further investigated, as there is now expected that the error originates form that calculation. From comparison of the previous cases can be concluded that the accuracy of the results was dependence on the chosen sensor points. So the inaccuracy of the calculation can be due to a near singularity in the matrix ε_p. The quantity of the singularity in the matrix can be determined with the condition number of the matrix, see section 3.4. To test this, procedure 0 was used with LC(150, 300, -200) and all the LU's(100). Different sensor elements were used to set up the ε_p matrix. Of these matrixes the condition number and the logarithm of the condition number are determined, as well as the solution of residuals. Some of the results are presented in table 5, in the order of smallest condition number to biggest. It is clearly seen that the condition of the

Table 5: Condition numbers and residuals of different cases

Case	Sensor points	Elements used	Residuals in Senor Element E11	E12	E22	Condition number of ε_p	LOG
0	3	2-1	0.00E+00	0.00E+00	0.00E+00	3.92	0.57
18	3	900-1	0.00E+00	0.00E+00	0.00E+00	5.35	0.73
11	3	550-1	0.00E+00	0.00E+00	0.00E+00	11.29	1.05
1	3	50-1	1.51E-09	1.69E-09	0.00E+00	20.33	1.31
21	3	1050-1	2.80E-09	-3.11E-09	2.28E-08	32.64	1.51
17	3	850-1	-1.73E-08	-9.31E-09	7.45E-08	63.82	1.80
13	3	650-1	-5.50E-09	1.16E-08	-1.75E-07	94.44	1.98
20	3	1000-1	-9.02E-09	1.96E-09	-3.58E-08	116.80	2.07
19	3	950-1	8.09E-09	1.54E-08	4.00E-08	264.41	2.42
8	3	400-1	-8.24E-08	6.03E-08	-1.40E-05	351.65	2.55
22	3	1100-1	-2.43E-07	-3.35E-07	-4.28E-08	583.21	2.77
5	3	250-1	1.68E-05	9.74E-06	-4.94E-05	1530.62	3.18
23	3	1150-1	-7.57E-08	-6.22E-07	7.19E-07	1994.26	3.30

matrix is of influence on the residuals of the calculation, when the condition number is low the residuals get better. It seems that the loss of significant digits has a big contribution on the error of the strain field of the SFEM.

The assumption is made that more sensor elements will reduce the error in the residuals. In the last investigation the number of sensor points that are needed to get the linear perturbation step residuals to zero is tested. For this case multiple the sensor points that are chosen that have a bad condition number more than 100, so this does not influence the results. Then the sensor points will be increased by one every calculation. This process is visualized in figure 9, where the residuals of the load factors and the root means square of the residuals of the strains are presented. It turns out you need 6 sensor points to get the residuals of this test to zero. Also the condition number improves with every sensor point added.
The poor conditioned matrix is clearly the biggest contributor to the residuals. So in further calculation this has to be minded.

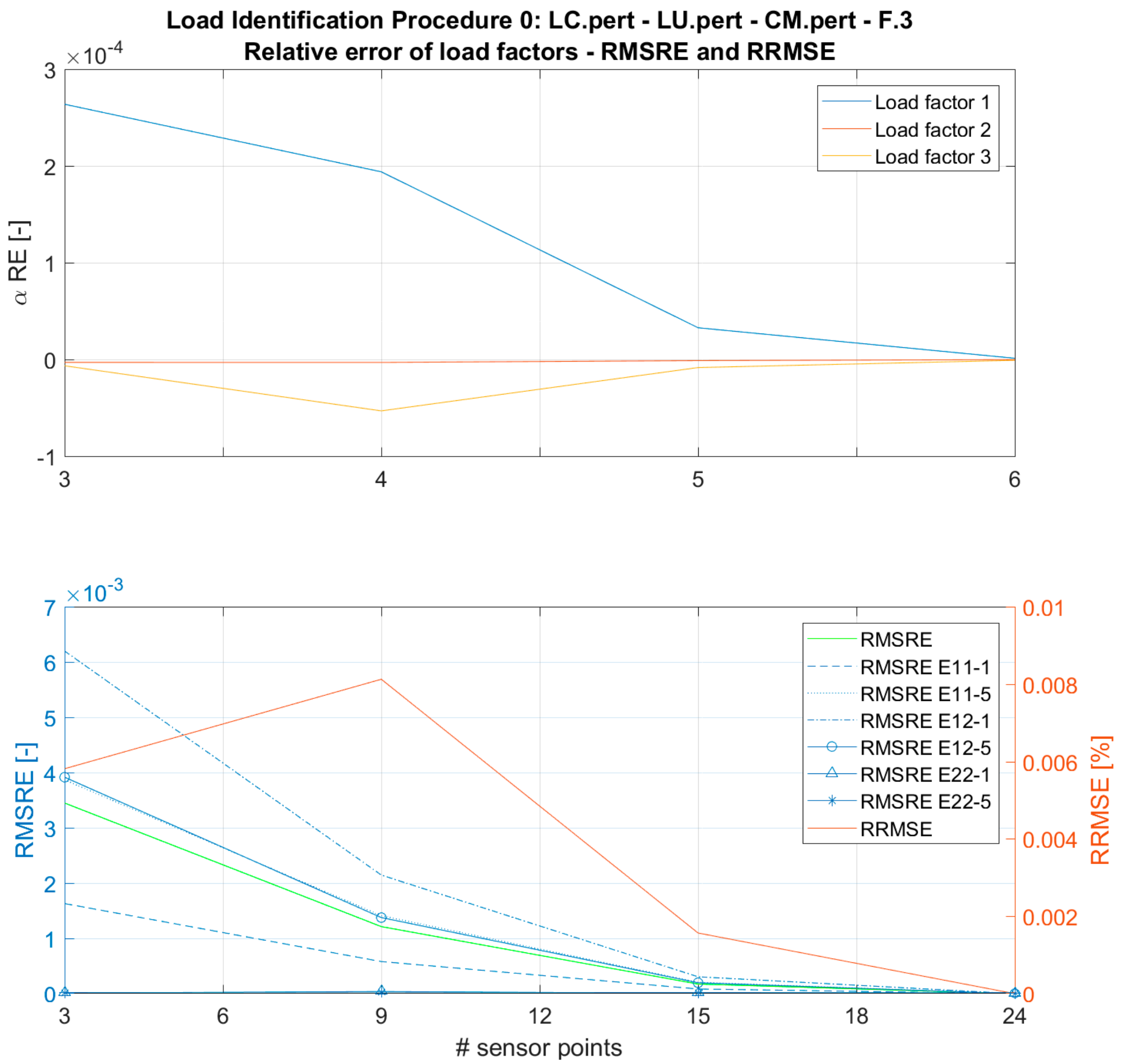

Figure 9: Load identification results of procedure 0

4.3 General nonlinear procedures (procedure 2, 3, 4 and 5)

In this section there is investigated what is the best nonlinear approach. This is done because the data in the DFEM will be of nonlinear nature. The following procedures will be carried out, with all nonlinear LC, but in each step different input data has a nonlinear behaviour.

- Procedure 2: LC – Nonlinear, LU – Linear, CM - Linear
- Procedure 3: LC – Nonlinear, LU – Linear, CM - Nonlinear
- Procedure 4: LC – Nonlinear, LU – Nonlinear, CM - Nonlinear
- Procedure 5: LC – Nonlinear, LU – Nonlinear, CM - Linear

Due to the nonlinearity in the LC the results can only be approximated and cannot be reached exactly. This means that there will always be strain residuals. Knowing this we will try to minimize this strain residual and the results of RMSRE and RRMSE will be use to give an indication of a good or bad solution. There will be a variable amount of sensor points used to minimize the strain residuals and find an optimum. The amount of sensor points lies between three and 300, because three is the minimum to get an answer in the load identification and more the a hundred different strain gauges in a very big test is unrealistic, with every strain gauges measuring in three directions, so 300 sensor points. the magnitude of the LC the forces were set on [15, 30, -20]. This is broad down regarding to the linear analyse in section 4.2, because of the unsuccessful nonlinear analyses that would otherwise occur in Abaqus. This results in a deformation of about 3mm, which is not much on a panel of 1.5 metre. The LU's were set on a magnitude of 10. Worth mentioning is that it was directly noticeable that nonlinear analyses take more time to calculated.

4.3.1 Procedure 2

In procedure 2 there is looked how good a nonlinear LC can be approximated by a linear LU and CM. The conclusion is that this is not really possible. Looking at figure 11, the load factors and the RRMSE that are being calculated give a reasonable match. The RMSRE on the other hand are way off. Looking at the strain data, LC has a couple of very low

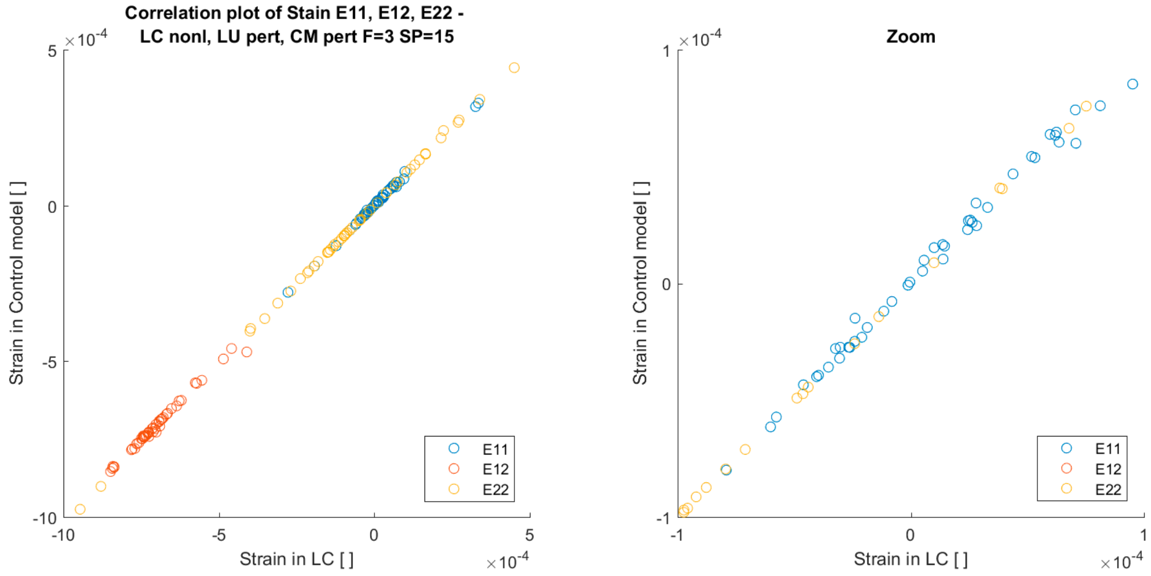

Figure 10: Correlation plot of procedure 2, with the strain values lower than 1e-6 left out

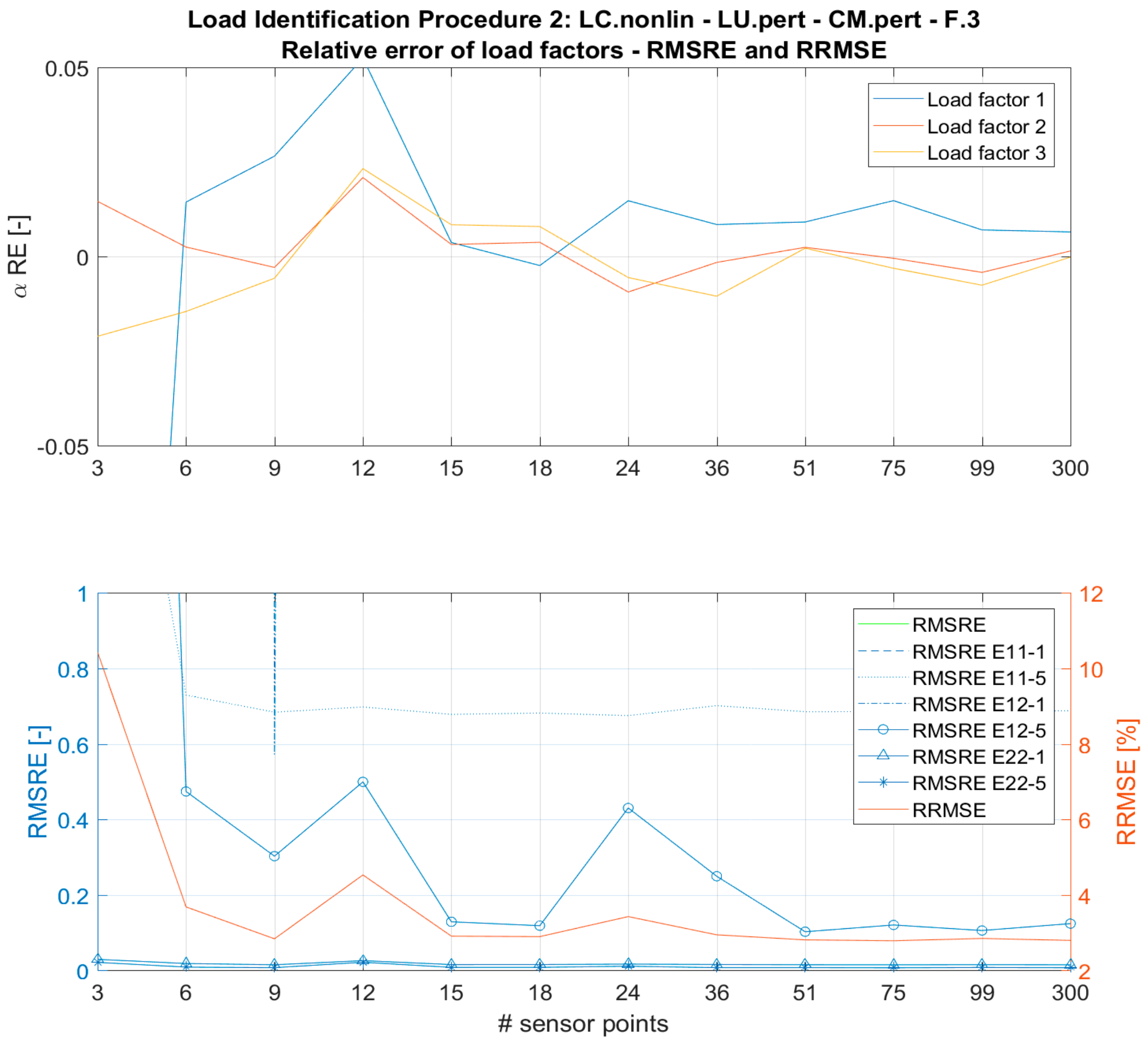

Figure 11: Load identification results of procedure 2

strain values in the order of 1e-7, while most of the strain values are between the orders of 1e-3 and 1e-5. If there is an error in those element, while using the RMSRE this result is big error values, this in combination with the fact that low strain values in LC not really contribute to the strain field, results in that LC strain elements that are under the absolut valure of 1e-6 are necelgted. This means 24 element get canceled from the total of 1156 elements, which is exeptable. This will be used in all the procedures of this section. That this improves the results can be concluded when looking at figure 12. They are still not good, but are more exeptable. To illustrated the difference between the correlation of the linear en no linear procedure figure 10 is compared with figure 8. In figure 10 the errors in the correlation are clearly noticeable.

Noticeable in figure 12 is that the residuals are converging to a certain ratio after the second case of increasing sensor elements. This result cannot be called good as the total RMSRE is 0.3 and it has to be 0.1 or lower to be fair. In figure 10 you can find the correlation plot of case with 15 sensors between the strains of LC and the strains of CM. Here you can clearly see that the results deviate from the centre line. In the case with 3 sensors the representation of the load factors is bad, so three sensor point are clearly not enough to approximated the nonlinear LC. This was expected. The relative error load factors are getting more accurate over time only is also sort of constant from the case with 15 sensor elements, this is not found in the RMSRE was it only improves in the first step. So the problem can be lying in the control model. As the CM is currently linear calculated, it could be that the linear control model of the SFEM is not a good representation of the nonlinear LC. So the next step will be to use a nonlinear CM to improve the result strain values.

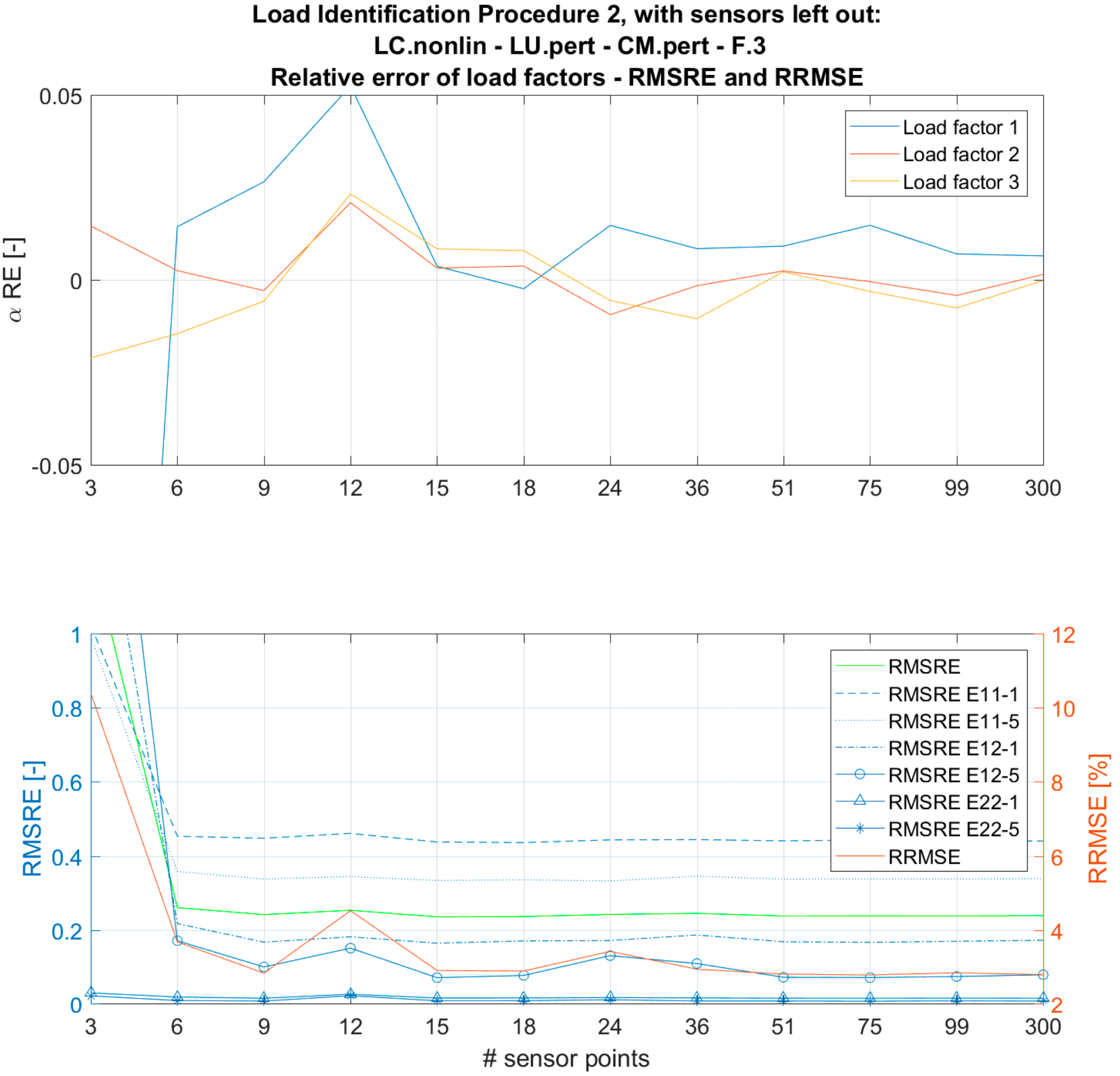

Figure 12: Load identification results of procedure 2, with the strain values lower than 1e-6 left out

4.3.2 Procedure 3:

To improve the strain field results of the CM, the values are calculated nonlinear. Figure 13 demonstrates a major improvement of the RMSRE. It is most of the time under the 0.1 so fair and at some point reaches the 0.01 ratio. With a little more improvement it should be possible to create a reliable reproduction. The load factors are in the same range as in procedure 2, which is obvious as the same linear LU's are used. Striking again is that more sensors not necessary concluded in more reliable load factors, but is somewhat constant when using more than six sensor elements. Using nonlinear LU's should yield improvement for the load factors, which in turn should yield further improvement on the strain residuals.

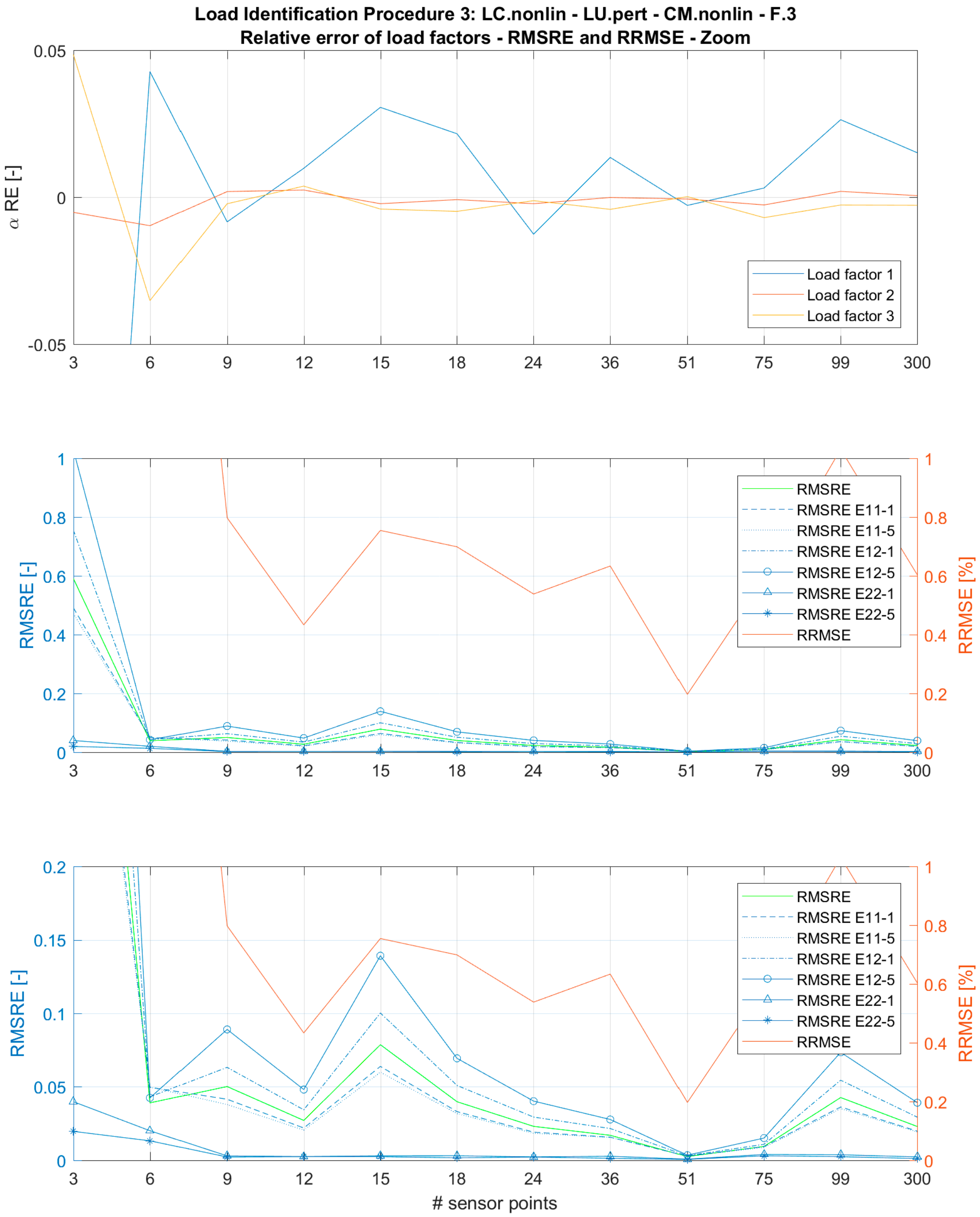

Figure 13: Load identification results of procedure 3

4.3.3 Procedure 4

Procedure 4 is the best reproducing of the nonlinear LC so far. The results can be found in figure 14. It is clearly seen that the error ratio of the load factors is much better and this applies also for the residuals ratio. But again the amount of sensors after 12 sensors does not increase the error results much. Remarkable is that for the case with 36 sensors there is an increase in the load factor error. A reason for the inaccuracy could be that two points close to each other with relative high differences in strains are used. Calculating the same 36 sensor element case with different sensor elements results in error ratio of the load factors: [-0.00863, -0.00201, -0.00319]. This is indeed in line with the error ratios of the other cases. So the peak can be due to the choice of elements. It is not due to the singularity of the matrix as the condition of the matrix is good, as in lower than 10.

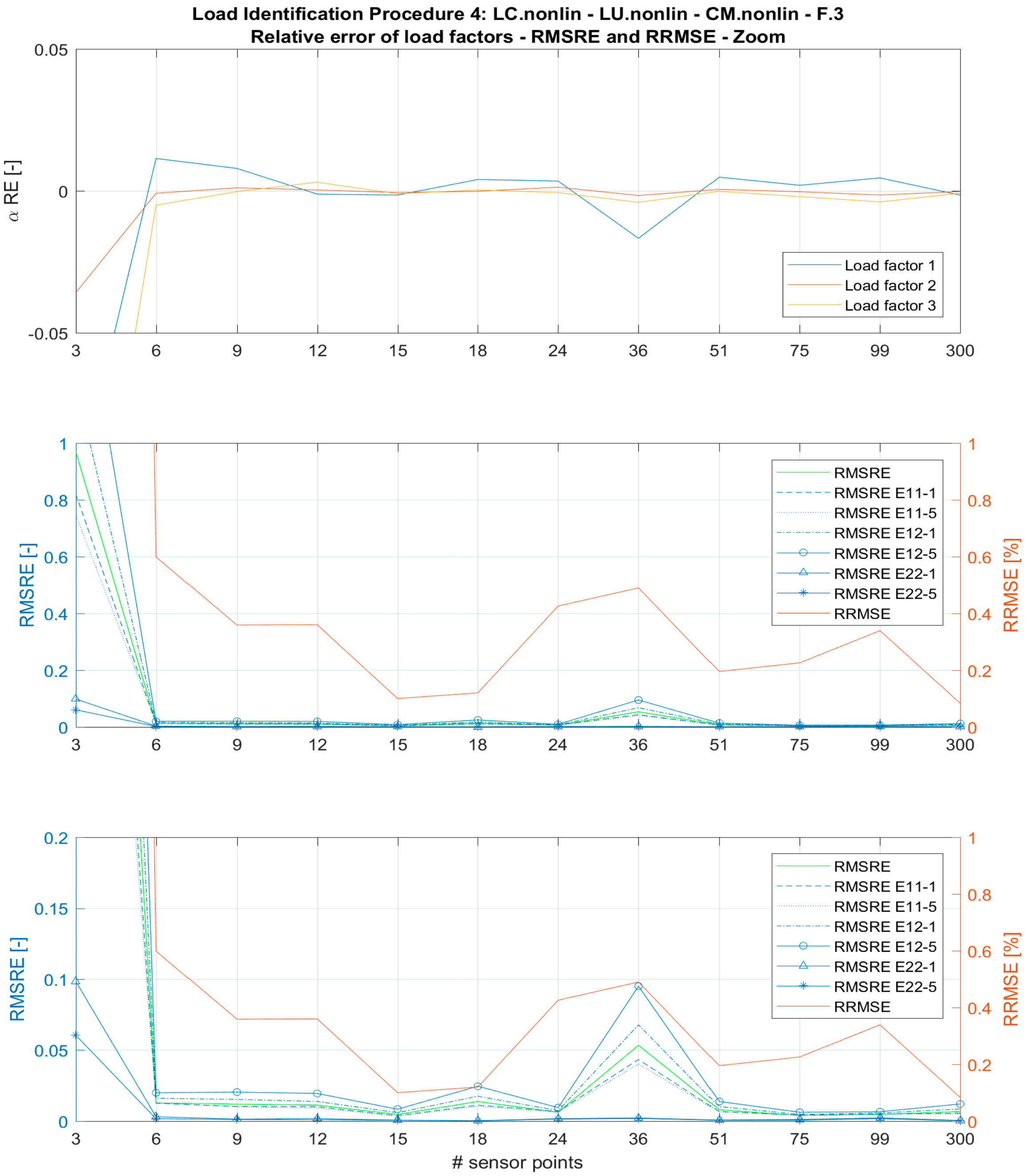

Figure 14: Load identification results of procedure 4

4.3.4 Procedure 5

To complete the available procedures, procedure 5 also ran. The assumption is made that the load factor should improve in comparison with procedure 2, but as in procedure 2 the strains are hold back by the linear CM. Looking at the end results it is almost the same as the results of procedure 2 as the residuals are constant within a ratio of max 0.5, see figure 15. When looking at the load factors a major improvement is noticeable in comparison with procedure 2. The assumption that was made is right. The conclusion can be made that nonlinear LU will represent the load factors of a nonlinear LC better than linear LU, but the strain residuals stay almost the same. So this error is due to the linear calculation of the CM.

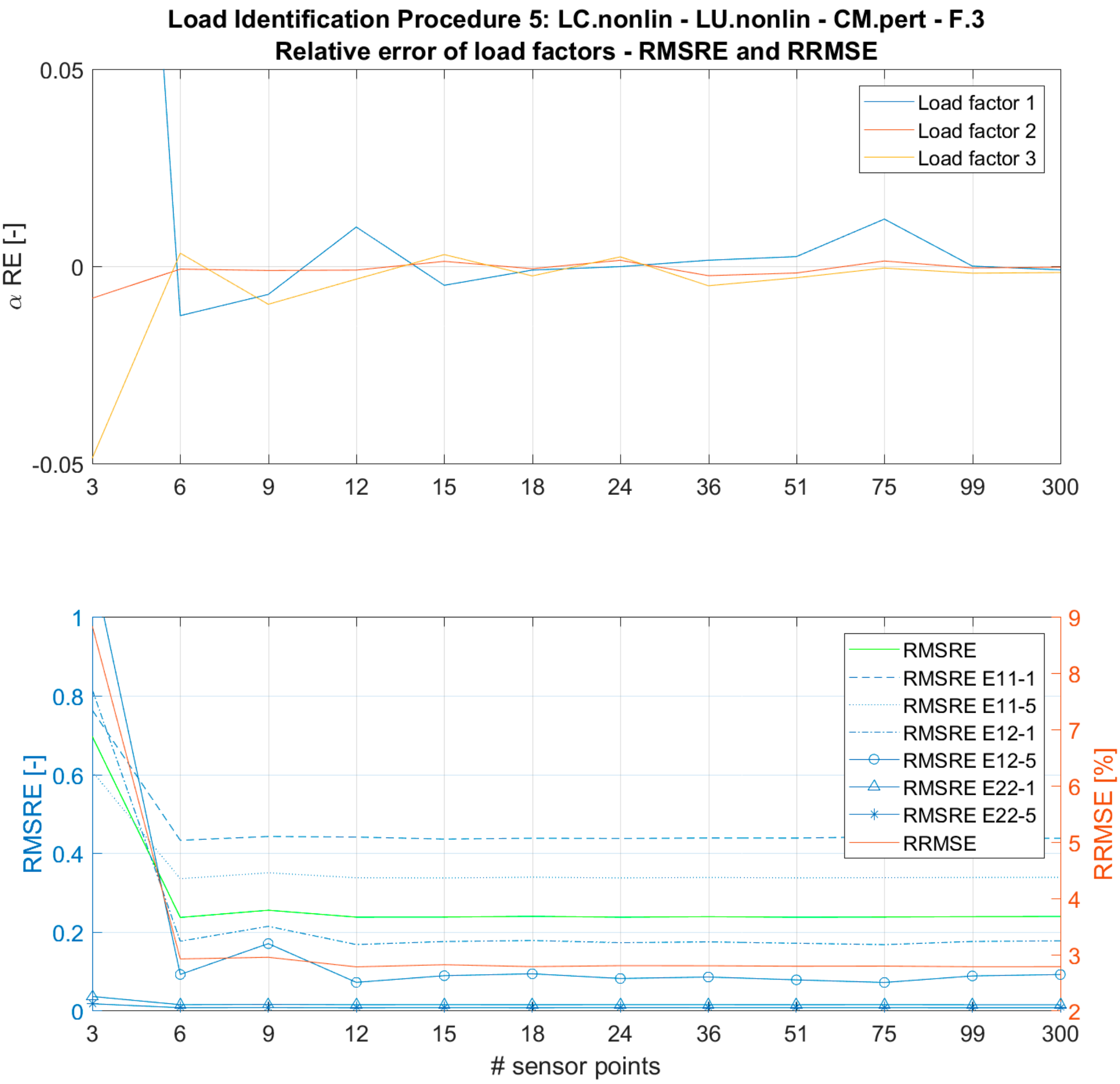

Figure 15: Load identification results of procedure 5

4.4 Linear and nonlinear procedures, with more than 3 loads.

The DFEM has 22 forces independent forces on the model. Here is investigated what happens if the amount of loads is increased, and so also the amount of LU. First the procedure 0 is used for the linear analyse and then procedure 4 is used to say something about the nonlinear analyse, as this is the most accurate nonlinear procedure.

4.4.1 Procedure 0

To calculate the SFEM with four loads, at least four sensors are necessary, with five loads at least five sensors and so on. To make the best comparison the same elements will be used for all loads calculations. Element 1-1 gives the first 3 sensor elements and from element 550 -1 a sensor point will be added if the amount of loads is increased. These elements are chosen because they had good results in element analyse in section 4.2. The extra loads will be placed on the loaded side of the panel. The side is divided in 1, 2, 3 or 4 parts to match the forces.
The results of the multi loads analyses are presented in table 6. It shows that the results for the load factors are good, but there can also be seen that more loads bring more insecurity in the model, higher relative error. Also the condition of the matrix is increasing, but this those not mean the residuals are worse. For case 0-F6 the condition number is 1161 and the $\log_{10}(1161) = 3.06$, which means that for single input in the worst case scenario five significant digits can be trusted. This is still acceptable, but certainly be watch out with higher amount of loads. Next up is the nonlinear multi forces procedures.

Table 6: Procedure 0 with variable amount of LC loads and LU's Loads

Procedure -forces		0-F3	0-F4	0-F5	0-F6
Forces		3	4	5	6
Sensor points		3	4	5	6
Sensor elements		1-1	1-1, 550-1	1-1, 550-1	1-1, 550-1
Matrix condition		8	197	247	1161
Alpha	$\alpha_1 = 1.5$	1.5000006	1.49993896	1.5000854	1.4999769
	$\alpha_4 = 2.5$		2.50000286	2.4999855	2.5000601
	$\alpha_5 = 0.5$			0.5000357	0.4998617
	$\alpha_6 = 2$				2.0000045
	$\alpha_2 = 3$	2.9999998	3.00000191	2.9999991	2.9999981
	$\alpha_3 = -2$	-1.9999999	-2	-1.9999907	-2.0000002
RMSRE	E11T	0.00E+00	1.50E-04	6.82E-05	2.10E-04
	E11B	0.00E+00	3.33E-04	9.33E-05	1.88E-04
	E12T	0.00E+00	5.86E-04	5.88E-05	8.06E-04
	E12B	0.00E+00	9.21E-05	1.11E-04	3.51E-04
	E22T	0.00E+00	5.43E-07	2.86E-06	2.57E-06
	E22B	0.00E+00	4.67E-07	1.92E-06	2.75E-06

4.4.2 Procedure 4

Figure 16, 17 and 18 present the results of 4, 5 and 6 loads on the procedure 4. From the 3 figures all are going to the a RMSRE level that is acceptable, though it takes some more sensor points. Also the condition number of cases are respectively in the order of 1e+16, 1e+2 and 1e+48. This means that the data from the cases with 4 and 6 forces could be complete rubbish and can only be trusted if it can be verified. As we can verify the strains for the CM and can said that they are not bad, there can be said that the load factors are reasonable. So this has no major effect on the results. Again can be concluded that adding more loads to the LC and LU results in more insecurities of the results.

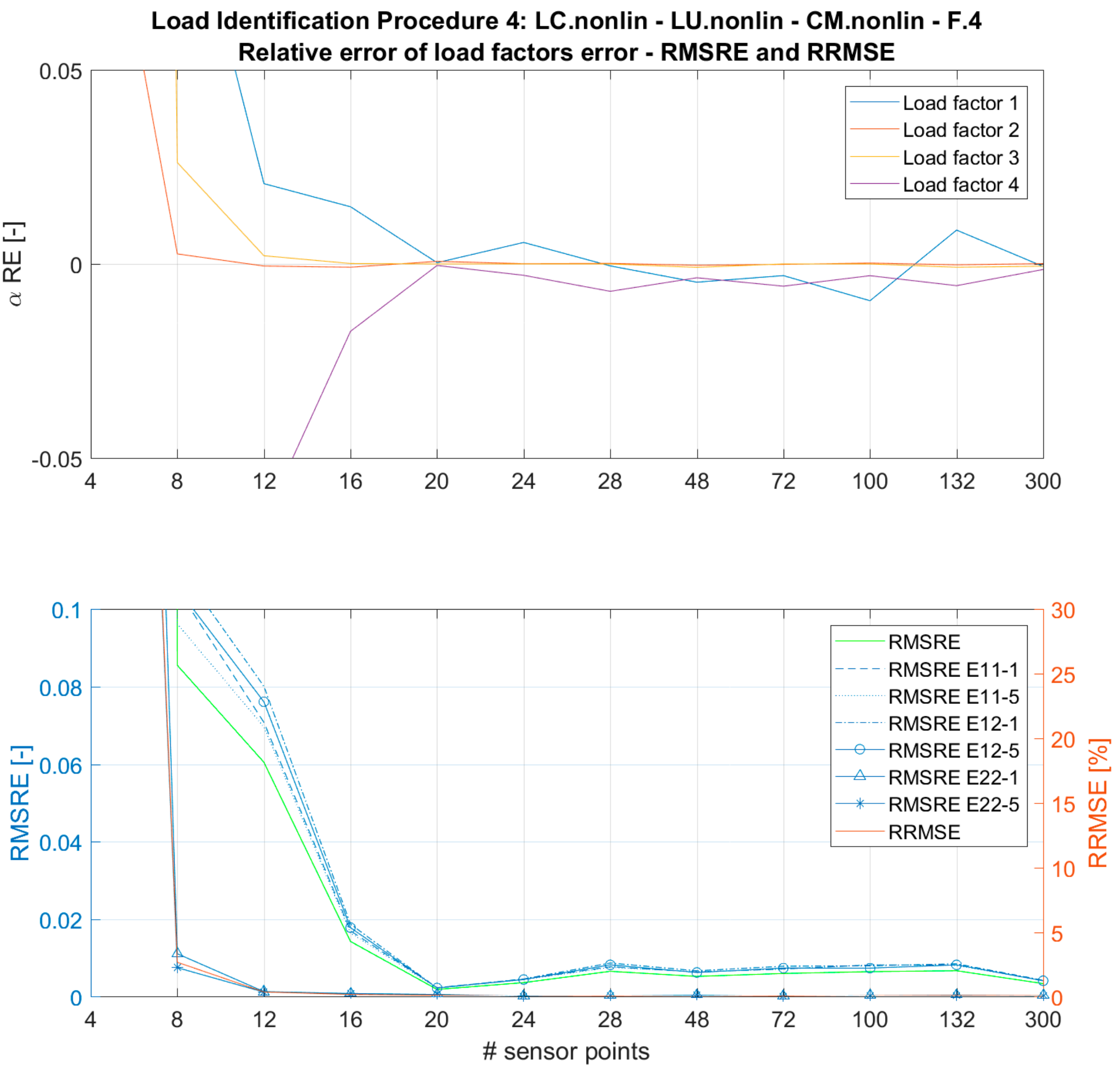

Figure: 16: Load identification results of procedure 4 with 4 loads

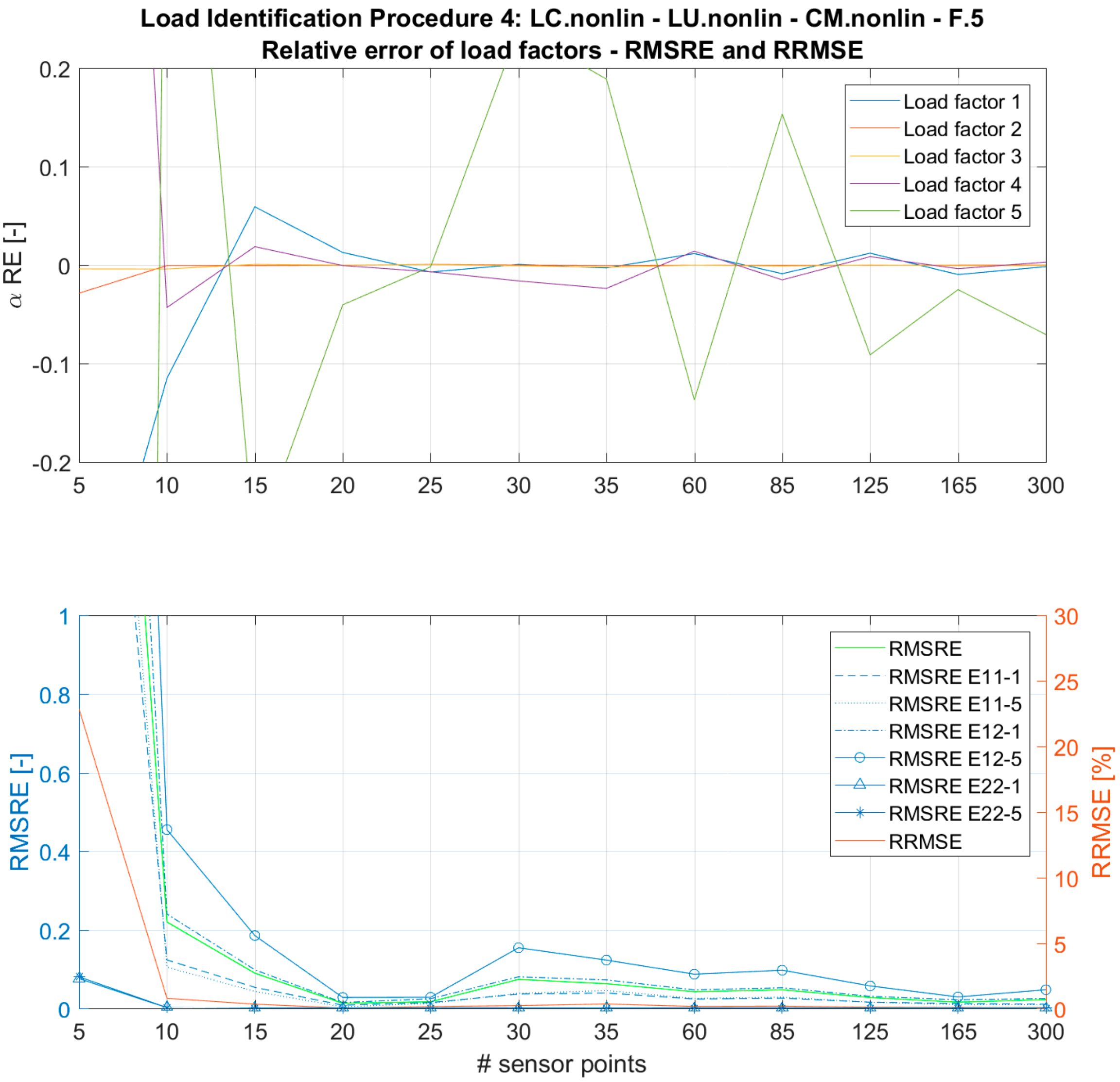

Figure: 17: Load identification results of procedure 4 with 5 loads

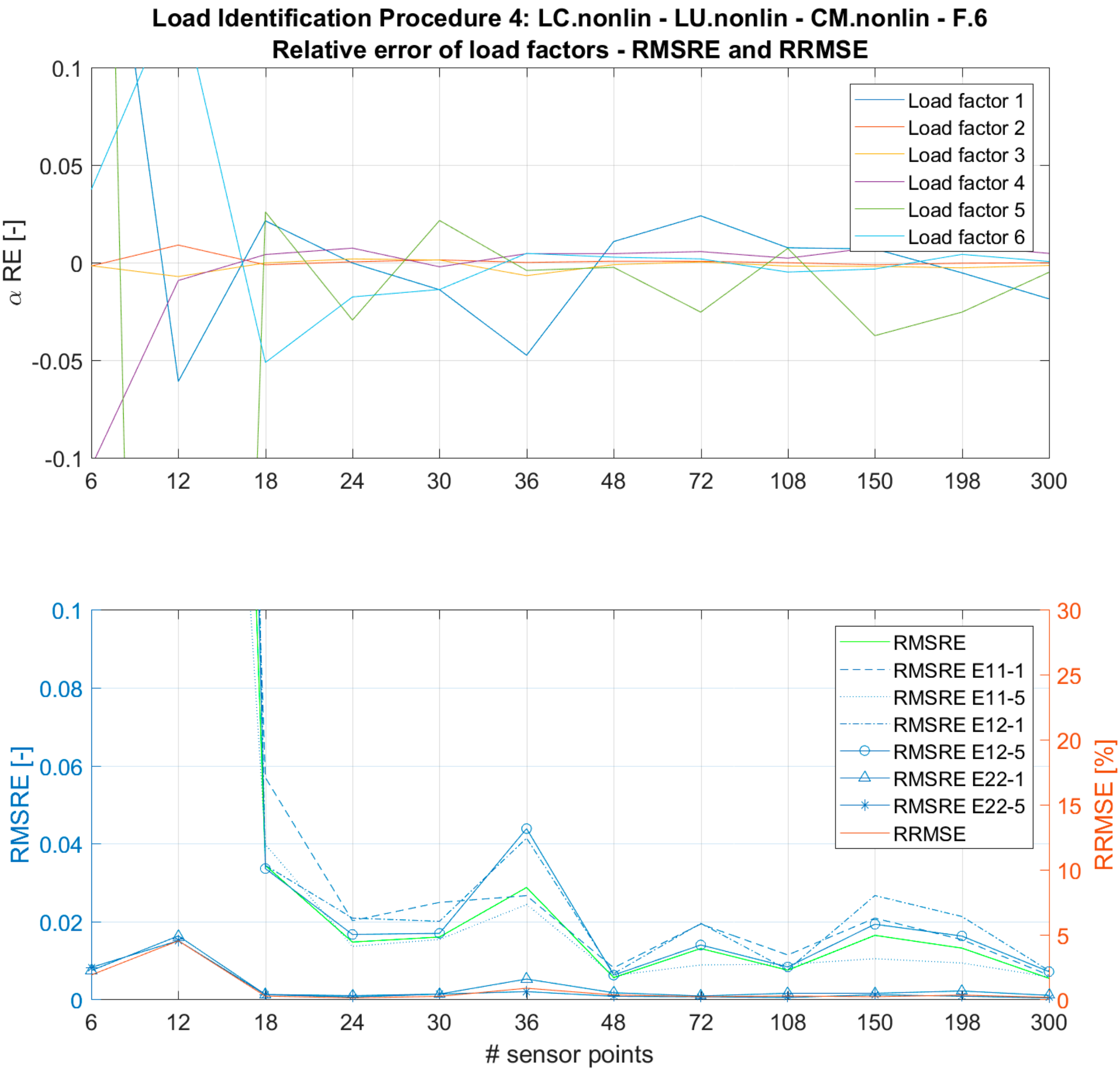

Figure: 18: Load identification results of procedure 4 with 6 loads

4.5 Effect of LU magnitude choices

Because the magnitude of LU can be chosen freely, the effect of this choice has to be determined. Better LU matrixes results in a positive influence on the strains of CM. All the measurement are done with procedure 4, so for nonlinear LC, LU and CM. The table 7 below presents the different LU magnitudes that are used. It turns out that it has no benefit to try to estimate the forces on the model. It even increases the results for the strain residual. Load force estimations in the same order will prove advantageous for the results. Further there is not must difference between the results.

Table 7: Results of procedure 4 with different LU's

Procedure - Case	4-0.LU1	4-0.LU2	4-0.LU3	4-0.LU4	4-0.LU5	4-0.LU6
Magnitude of LU						
LUF1	1	14.99	15.0617427	0.1	10	5
LUF2	1	29.99	29.8906459	0.1	10	5
LUF3	1	-19.9	-20.035081	0.1	10	5
Load factors expected						
A1	15	1.00067	0.98809	150	1.5	3
A2	30	1.00033	0.99841	300	3	6
A3	-20	1.0050	-1.00978	-200	-2	-4
Load factors						
A1	15.06174	1.01201892	1.00790656	150.762283	1.49026453	2.99896932
A2	29.89065	1.00209594	1.00525737	298.856201	2.99589896	5.98329639
A3	-20.0351	0.9909566	0.98858029	-200.36250	-2.0027091	-4.0061197
CMF1	15.06174	15.1701636	15.1808	15.0762283	14.9026453	14.9948466
CMF2	29.89065	30.0528572	30.0478	29.8856201	29.9589896	29.9164819
CMF3	-20.0351	-19.720036	-19.8063	-20.036250	-20.027091	-20.030598
Deviation from LC Forces.						
CMF1 – LCF1	0.061743	0.17016361	0.18082935	0.07622833	-0.0973547	-0.0051534
CMF2 – LCF2	-0.10935	0.05285724	0.04779216	-0.1143798	-0.0410104	-0.0835180
CMF3 – LCF3	-0.03508	0.27996366	0.19371296	-0.0362503	-0.0270915	-0.0305986
Matrix condition	4.089272	7.19413904	7.14154576	4.09019495	4.07740564	4.08461455
Average Residual	3.17E-04	3.17E-04	3.17E-04	3.17E-04	3.17E-04	3.17E-04
RMSE total	2.94E-06	4.38E-06	4.34E-06	3.07E-06	1.37E-06	2.29E-06
RMSE:						
E11T	1.32E-06	1.92E-06	1.90E-06	1.18E-06	5.49E-07	8.90E-07
E11B	9.80E-07	2.09E-06	2.08E-06	1.27E-06	6.05E-07	9.63E-07
E12T	3.10E-06	2.99E-06	2.92E-06	3.15E-06	1.24E-06	2.33E-06
E12B	3.07E-06	2.82E-06	2.75E-06	3.09E-06	1.19E-06	2.28E-06
E22T	4.21E-06	6.67E-06	6.62E-06	4.14E-06	1.92E-06	3.10E-06
E22B	3.59E-06	6.78E-06	6.73E-06	4.10E-06	1.97E-06	3.11E-06

4.6 Conclusion of chapter 4

The reproduction of a linear LC is good with the used method, though the residuals were not going exactly to zero. The biggest error contributor was the condition number of the ε_p matrix. This number should be low, as it can cause errors in the calculation of the load factors. To improve the condition number and the solution of the load identification extra sensor element can be added. In the nonlinear calculation it appeared that low strain values of LC should be neglected as they significantly increase the error of the model and are not very relevant for the recreation of the strain field as they are small. Procedure 4 was by far the best to reproduce the strain field of the nonlinear LC. This procedure result is a good representation of the strain field of the nonlinear LC. Also there was found that increasing the number of load creates more insecurity for the solution, but still result in fair till good results. The choice of magnitude of the LU's seems not to influence the result of the load identification.

5 Detailed Finite Element Model (DFEM)

To further research the behaviour of the load identification on a FE model, the DFEM will be investigated. To begin the behaviour of the linear perturbation step is tested (procedure 0) and secondly to perform a nonlinear identification procedure 4 is used as this was the most accurate in the SFEM. Other information won in the previous chapter will of course be considered. So will be looked at the time to run a DFEM and concluded that it is also worth looking into procedure 2 for the nonlinear LC. This is because it is significantly faster to run.
The strain data that is used has a ‘double data’ precision, this means it has an accuracy of the order 1e-16. With this high order of accuracy there is less chance that during the solving of the load identification problems arise.
In this chapter two different LC will be approached, which are named LC.1 and LC.2. LC.2 has a five times higher magnitude of the loads as the loads of the LC.1. With three different sets of LU’s, this will give in total six configuration on with load identification can be performed. The RMSRE and the RRMSE will be used to evaluate the CM and to conclude on the solutions.

5.1 Procedure 0

Starting with the linear perturbation step with loads that were given by NLR of perform a bending on the model, the load factors that are trying to achieve in the different cases can be found in table 8. As previously mentioned this linear perturbation step load identification should result in an exact calculation of these load factors. For the linear analyses the LU.3 will be left out of the calculation.

Table 8: Load factors to achieve

	LC1			LC2		
Loads	LU1	LU2	LU3	LU1	LU2	LU3
Fx	5	0,2	0,2	25	1	1
Fy	-2	0,2	0,1	-10	1	0,5
Fz	-3	0,2	0,1	-12,5	1	0,5
Mx	4	0,2	0,2	20	1	1
My	7	0,4	0,4	35	2	2
Mz	2	0,2	0,2	10	1	1
Frame spreader moment	1	0,2	0,2	5	1	1
Skin spreader force	1,5	0,2	0,2	7,5	1	1
forces on cross-beams 70, 71, 75, 76	1	0,2	0,1	5	1	0,5
forces on cross-beams 72	10	0,2	0,1	50	1	0,5
forces on cross-beams 73	5	0,2	0,1	25	1	0,5
forces on cross-beams 74	5	0,2	0,1	25	1	0,5
moments on cross-beams 70, 71, 75, 76	1	0,2	0,2	5	1	1
moments on cross-beams 72	0,2	0,2	0,1	1	1	0,5
moments on cross-beams 73	0,2	0,2	0,2	1	1	1
moments on cross-beams 74	0,2	0,2	0,2	1	1	1

In the conclusion of the SFEM analysis was stated that the low values of strains in LC give a relative high error while they are not very interesting for the result as they are low strains so have little impact on the total strain field. For this reason the low values are left out, a strains is considered low when it is lower than the 0.1 times mean of all the LC strains. For the strains of LC.1 this means that the average strain is 1.838e-04, with a range of the absolute values from 6e-7 till 1.8e-3, but al values outside the range of -1.838e-5 and 1.838e-5 will be neglected.

Cases with 22 sensors

The analysis on the DFEM is started with a case of 22 sensors, the same amount as the LU's. The first results indicate that the answer of the load identification is highly sensor location depended. To show this there are two cases performed. In the first case a load identification with 22 selected sensors with close proximity to each other is performed. In the second case a load identification with sensors that are spread throughout the DFEM is performed. Both results of the cases can be found in table 9.

Table 9: Load identification results procedure 0 DFEM

Procedure	0 [s22] - close	0 [s22] - spread
Condition number	2.99E+07	3.590e+03
RMS-re selected sensors	2.640e-20	5.937e-11
RMS-re all sensors	1.465	2.927e-05

Though for the case of close sensor element most of the load factors are somewhere in the area they should be, but a couple are way off. This result in high precision recreation of the selected sensor, but the recreation of the complete strain field is rather poor. For the spread selected sensors the load factors are better, which is reflected in the results of the strain fields. The strains field of the selected sensors is less accurate than the previous case, but the overall strains field is a better representation of the LC.

Cases with more sensors

From the SFEM there is known that using more sensors increases the accuracy of the solution. Appling this to the DFEM linear model results in figure 21. Looking at figure 21 it can clearly be seen that adding sensors will increase the accuracy further.

To look at the influence of the spread in the sensors there are three cases set up. In the cases the sensor that are used are lying on different parts of not closer together than 0, 10, 100 or 500 millimetre. The RRMSE of the results can be found in the figure 19. Two things are noticeable the first one is that using all the sensors results in the smallest error. The second one is that there is a significant loss of sensor point when using the restriction on the distance. So there are a lot of sensor elements that are close together.

In introduction of this paper was said that a big test contains about 100 senor elements. Limiting the amount of sensor elements to 100 sensor elements, gives figure 20. In this case the distance between the elements has a positive effect on the error. Though this is one case, the result is highly dependent on the randomly chosen elements. There were case where the 0 distance gave the best results, but there are significantly more case where the 100 millimetre sensor distance gives the best result.

Concluding the sensor choice use always as many sensor point as available, in this case to increase the change of a good solution and decrease the amount of senor element to about 150. The choice is made to use the 100 millimetre distance between sensor elements in the further calculations.

Now that some variables are established, we go back to the linear load identification over multiple sensors presented in figure 21. The frame spreaders are the worst in reproducing there load factor, especially frame spreader moment on 70, 71, 75 and 76. When increasing the amount of sensor element the relative error of the load factor is significantly improving as is the RMSRE and the RRMSE. The end result is that all of the cases in this analysis result in excellent representation of the LC-1 strain field, but the last case gives the best result.

The other LC and LU's are investigated and the results can be found in figure 21 till 24. It can be seen that the calculation of LC.1 are better represented by LU.1 and LC.2 better by LU.2. The results of LC.1 with LU.2 and LC.2 with LU.1 also give a good solution of the problem.

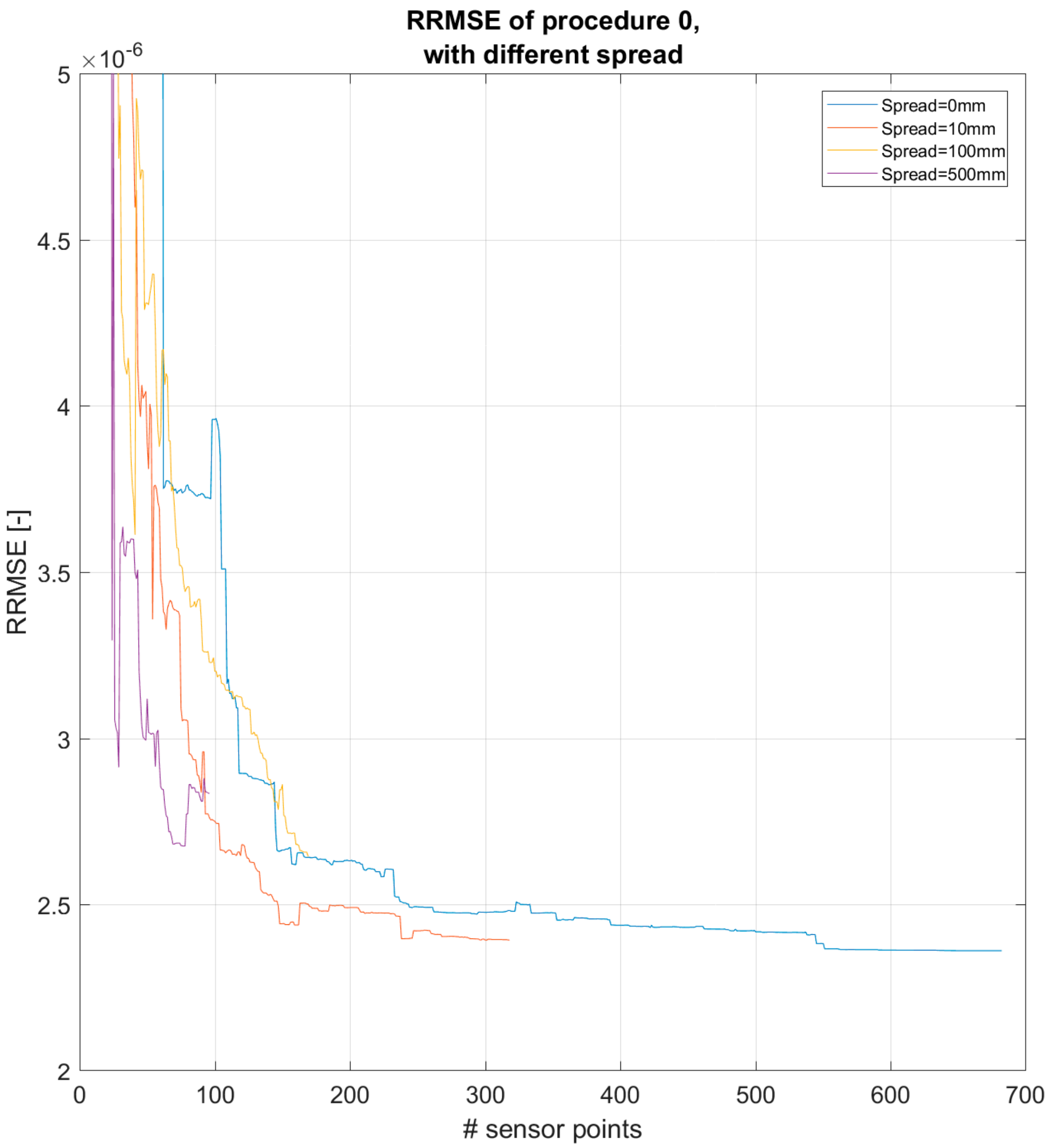

Figure 19: RRMSE results of procedure 0 with different sensors distances

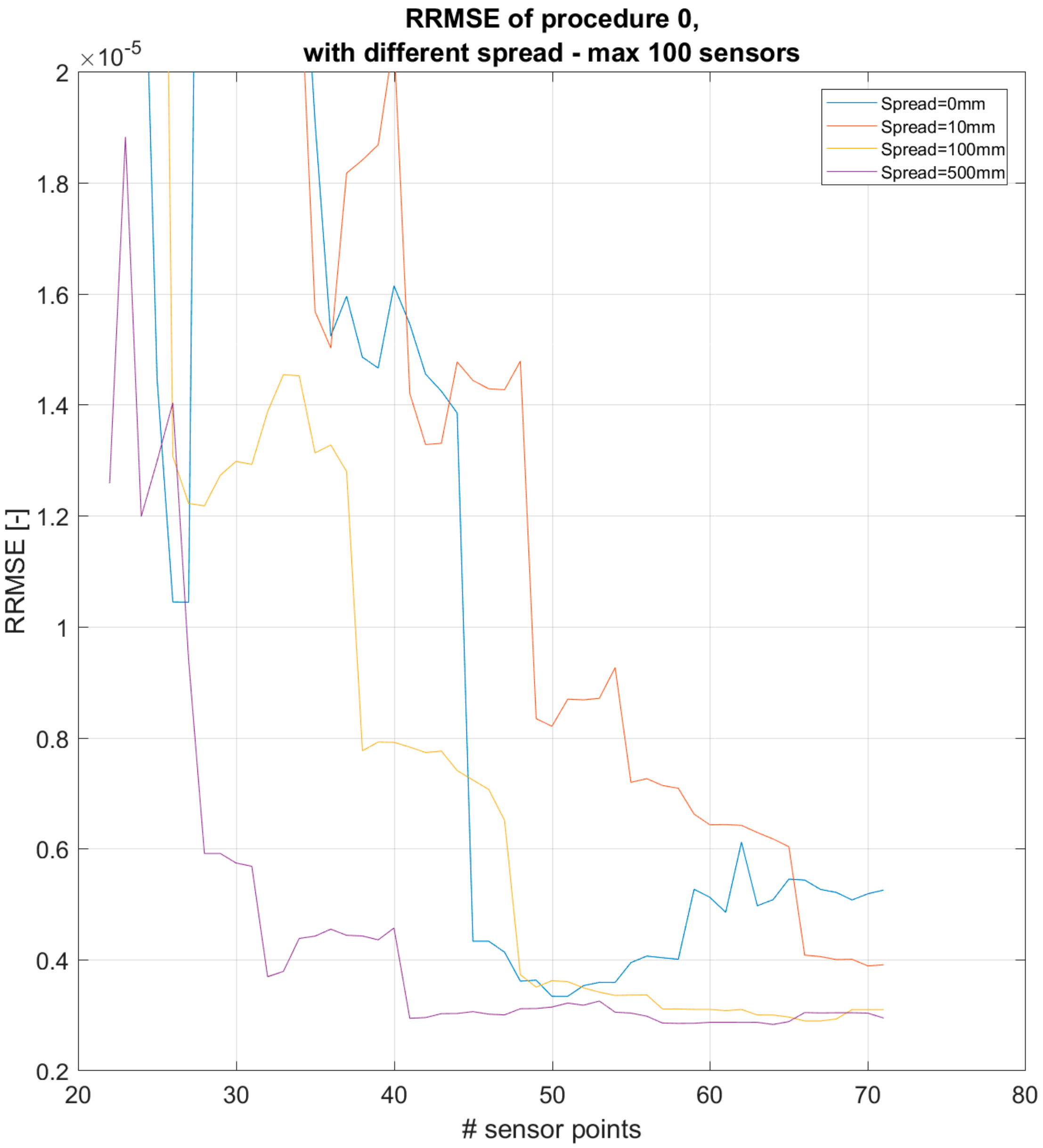

Figure 20: RRMSE results of procedure 0 with different sensors distances and a maximum of 100 sensors

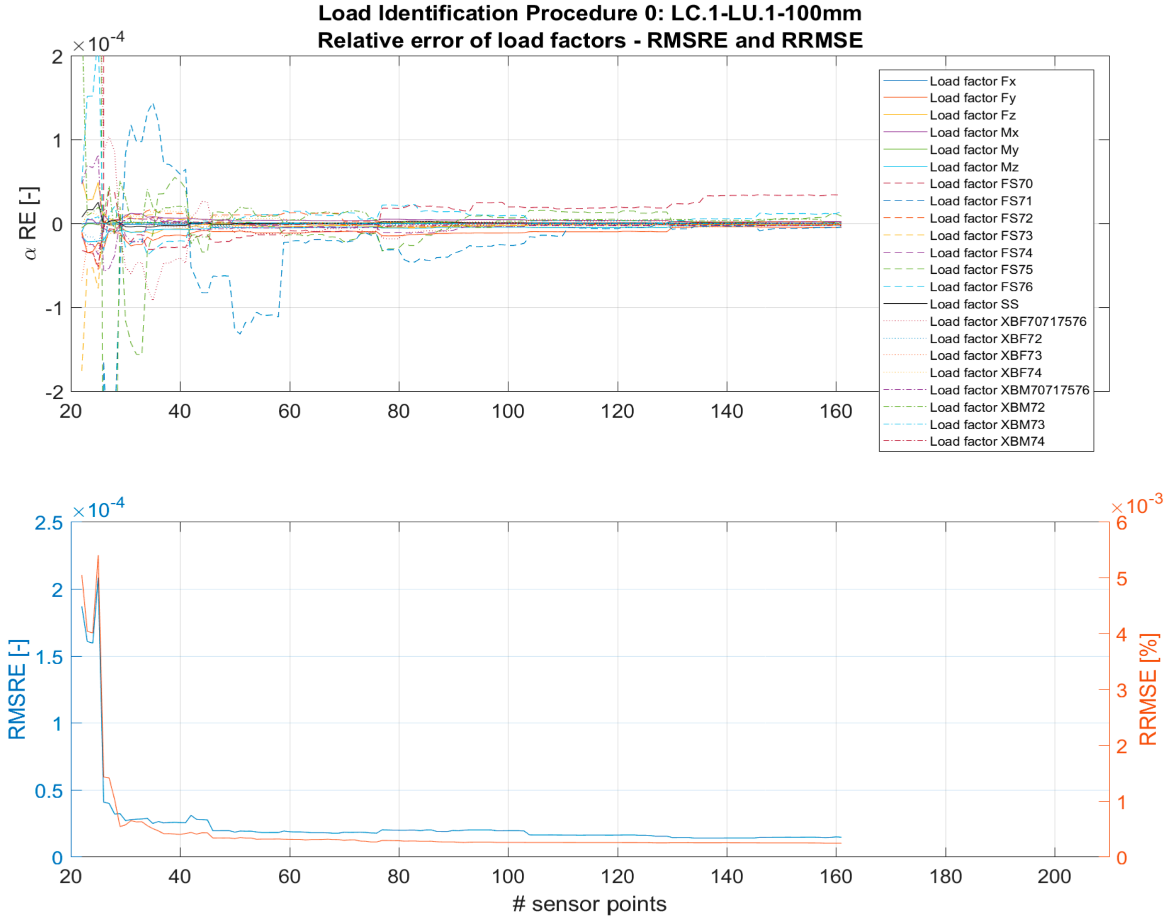

Figure 21: Load identification results of procedure 0 – LC.1 LU.1

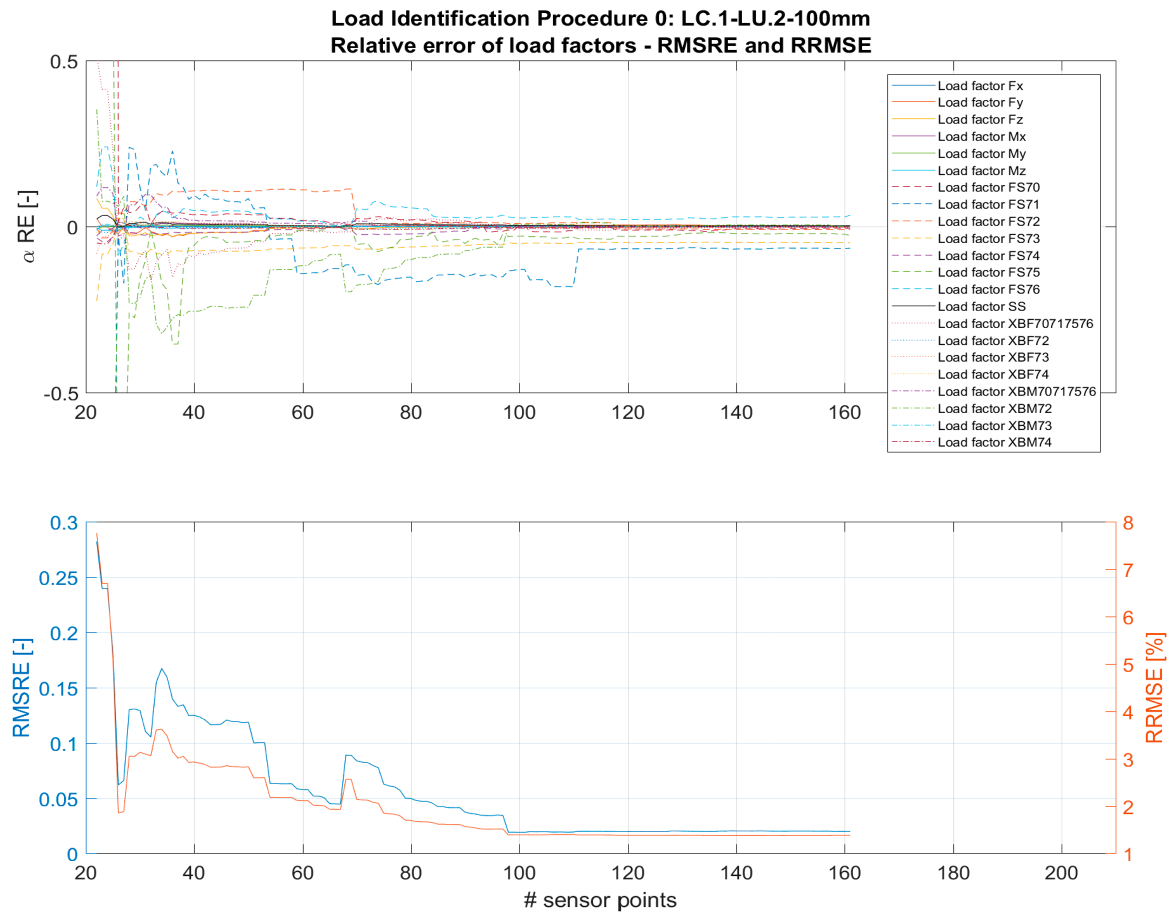

Figure 22: Load identification results of procedure 0 – LC.1 LU.2

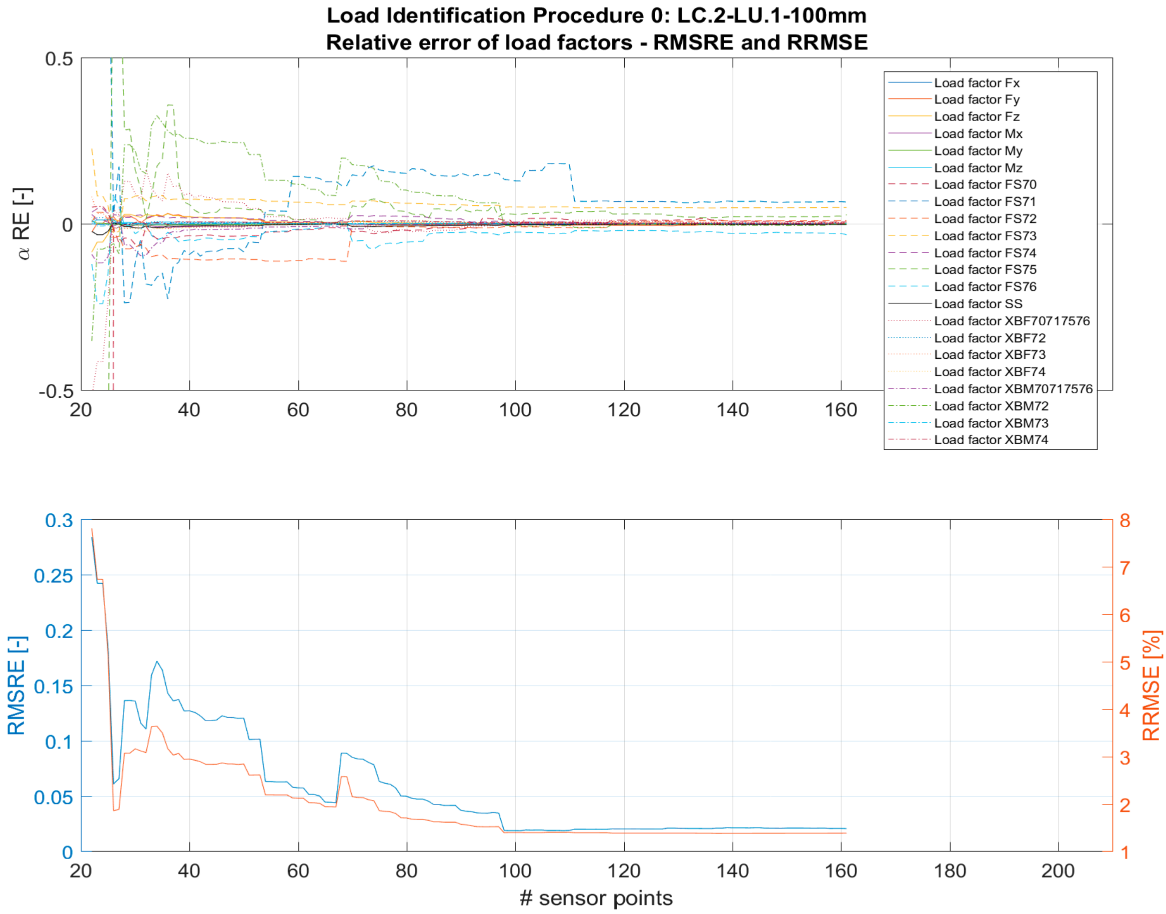

Figure 23: Load identification results of procedure 0 – LC.2 LU.1

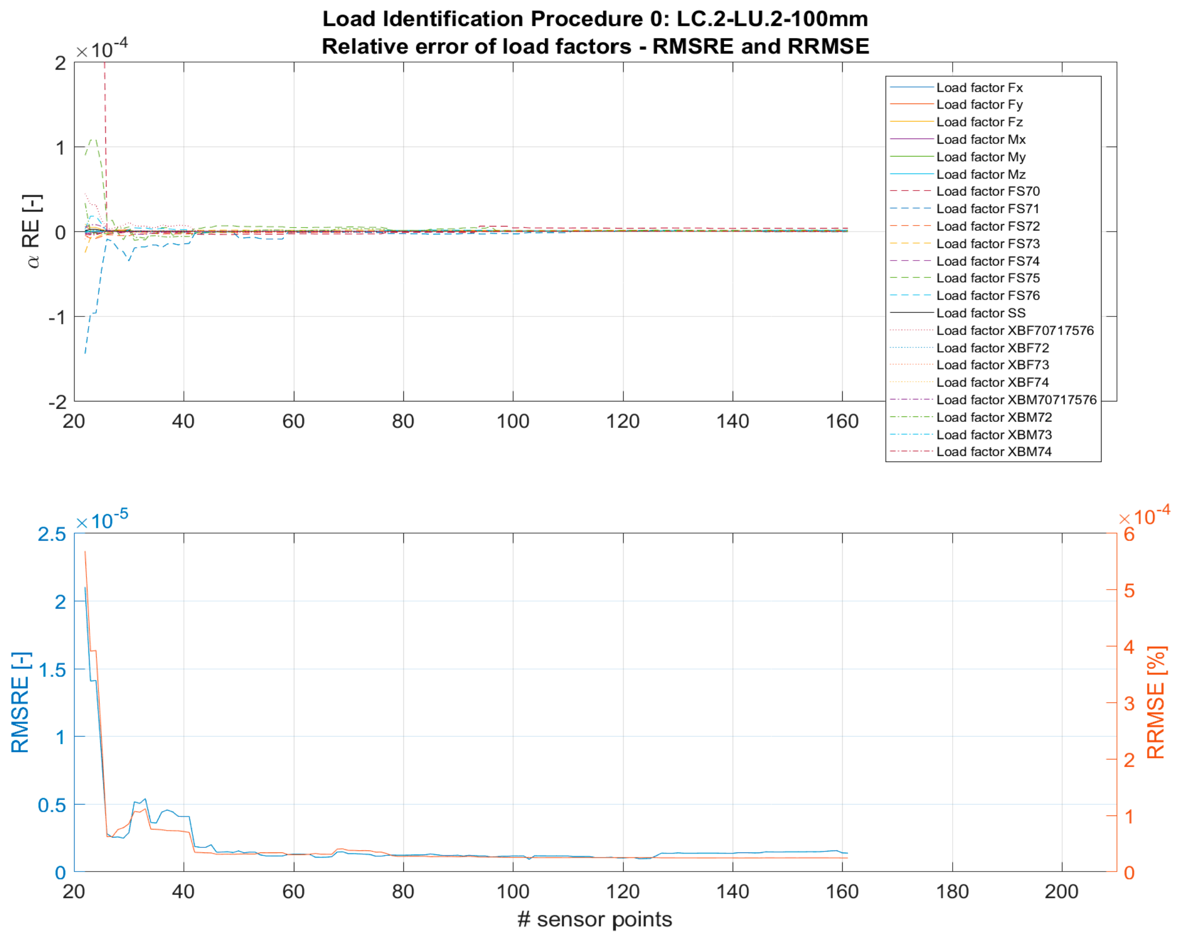

Figure 24: Load identification results of procedure 0 – LC.2 LU.2

5.2 Procedure 2

If a nonlinear strain field can be identified with linear LU, we would benefit of the fast and low cost calculation of linear modelling. Although the SFEM study shows this in not promising, it is tested. The magnitudes of load of nonlinear LC.1 are used, with the LU.1 loads.
The conclusion of this load identification analysis is that it is pretty bad, see figure 25. The load factors relative error is nowhere near zero. The RMSRE is also terrible. The RRMSE did give values but the best error is around 200%. This means that following section 3.3 (very value higher than 30 is poor) this is a poor representation. So it is not possible to calculate the nonlinear DFEM LC with the linear LU's.

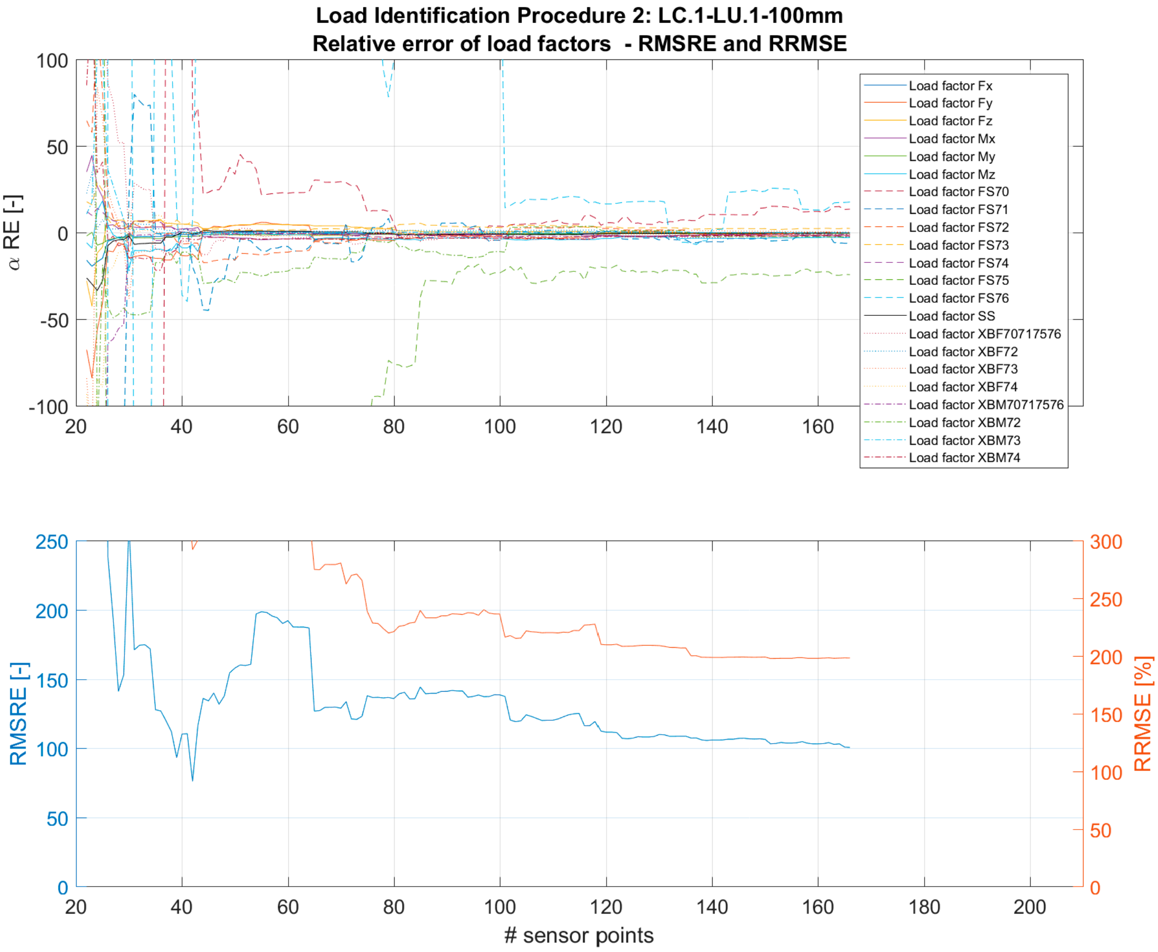

Figure 25: Load identification results of procedure 2 – LC.1 LU.1

5.3 Procedure 4

The calculation of the nonlinear LU the frame spreaders did not wanted the get calculated individually, so they are taken as one LU. This leaves 16 individual LU's. In figure 26 till 31 the load identification over multiple sensor elements of all the six load identifications configuration the properties are given in the introduction of this chapter. In all six configurations the case with the most sensors (the last case) gives the best relative error of the load factor.
To get the results for the nonlinear CM the model has to be run though Abaqus, because of the time consuming process of this, as some calculation took more than 12 hours, one specific CM models was chosen for every configuration. The RMSRE and the RRMSE of residuals can be found in table 9. From this result can be concluded that only LC2-LU1 is acceptable in the RRMSE, but for none of the configuration the RMSRE gives fair results. So there is no good representation of the nonlinear DFEM LC.

Table 9: Load identification results of the six configurations

Case	RMSRE	RRMSE
LC.1-LU.1	2,1914	932
LC.1-LU.2	2,4514	860
LC.1-LU.3	2,1836	864
LC.2-LU.1	0,2675	7
LC.2-LU.2	0,5755	270
LC.2-LU.3	0,6327	182

Despite of a poor solution the different configuration can be compared to each other. For the LC.2 there are clearly better result than for the LC.1 configuration. A possible explanation for this is the use of higher magnitude of loads, it causes more nonlinear behaviour of the DFEM. So maybe the deformation of 1 mm in the LC.1 is not causing significate strains. There can be concluded that the set of LU is despite of earlier found in section 4.5 of influence on the results of the nonlinear solution.
Further noticeable is the relation between the load factors and the RMSRE. The better the representation of the load factors the better the RMSRE. This does not have to be the case in the nonlinear load identification but is seem it is in this case.

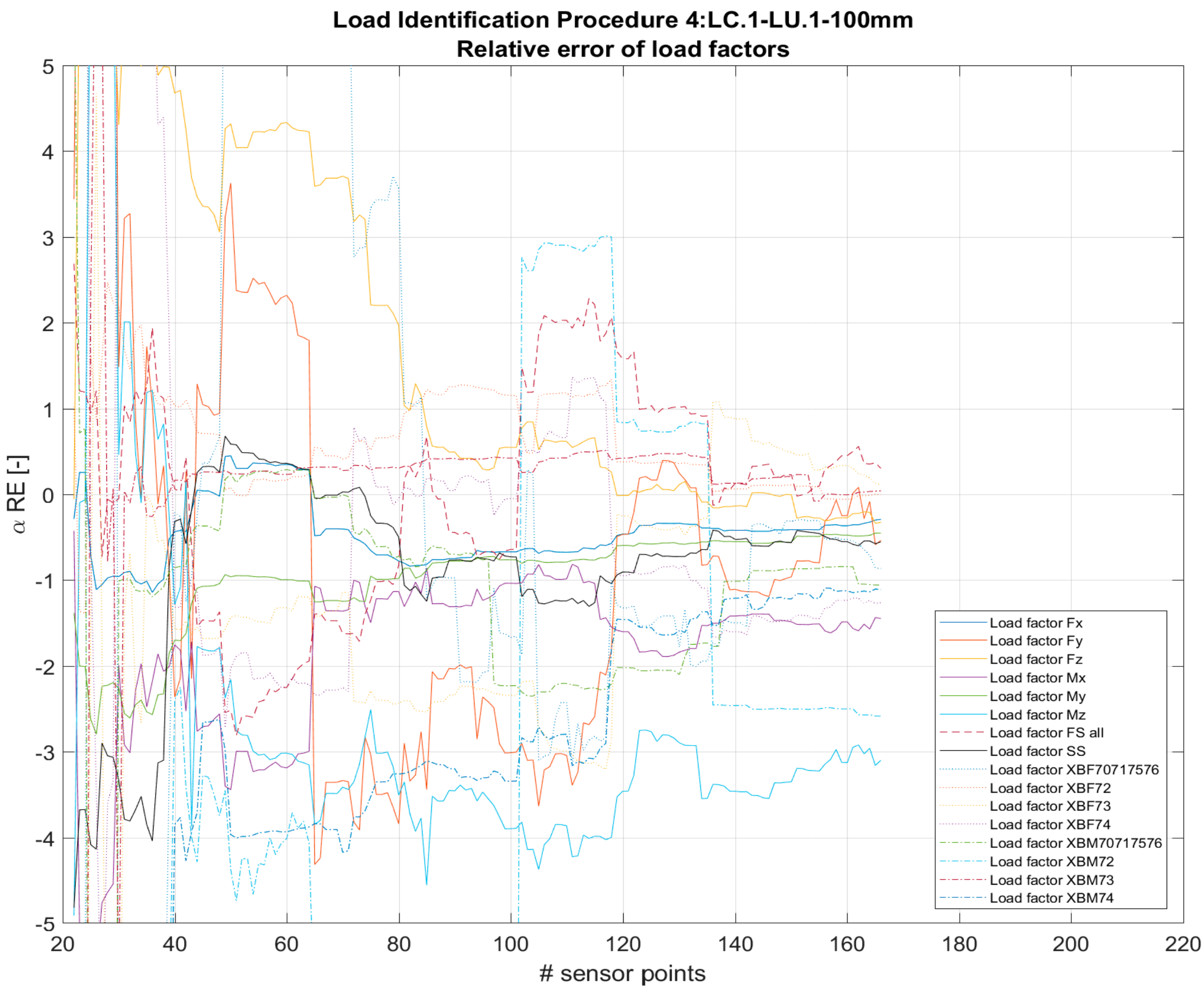

Figure 26: Load identification results of procedure 4 – LC.1 LU.1

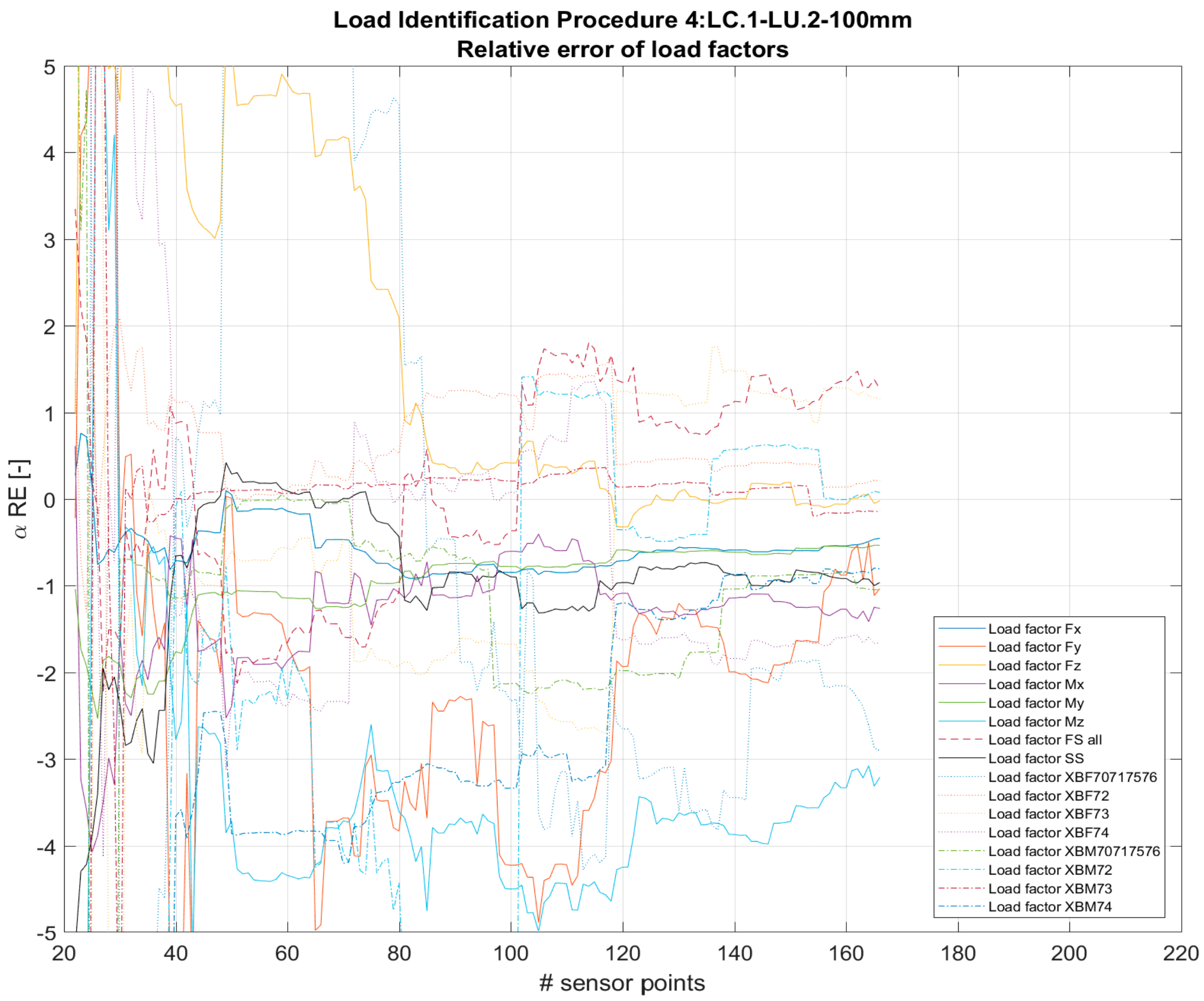

Figure 27: Load identification results of procedure 4 – LC.1 LU.2

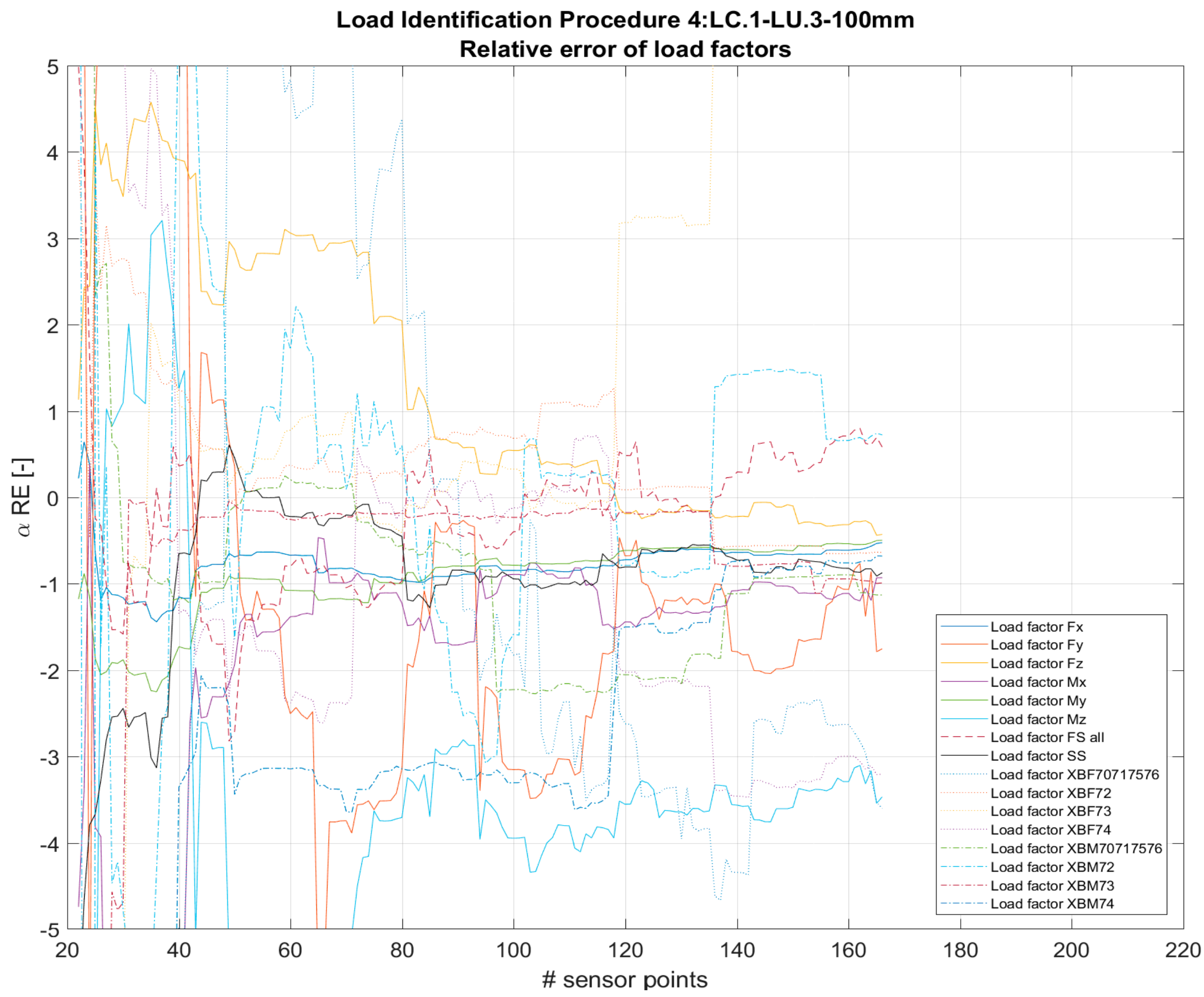

Figure 28: Load identification results of procedure 4 – LC.1 LU.3

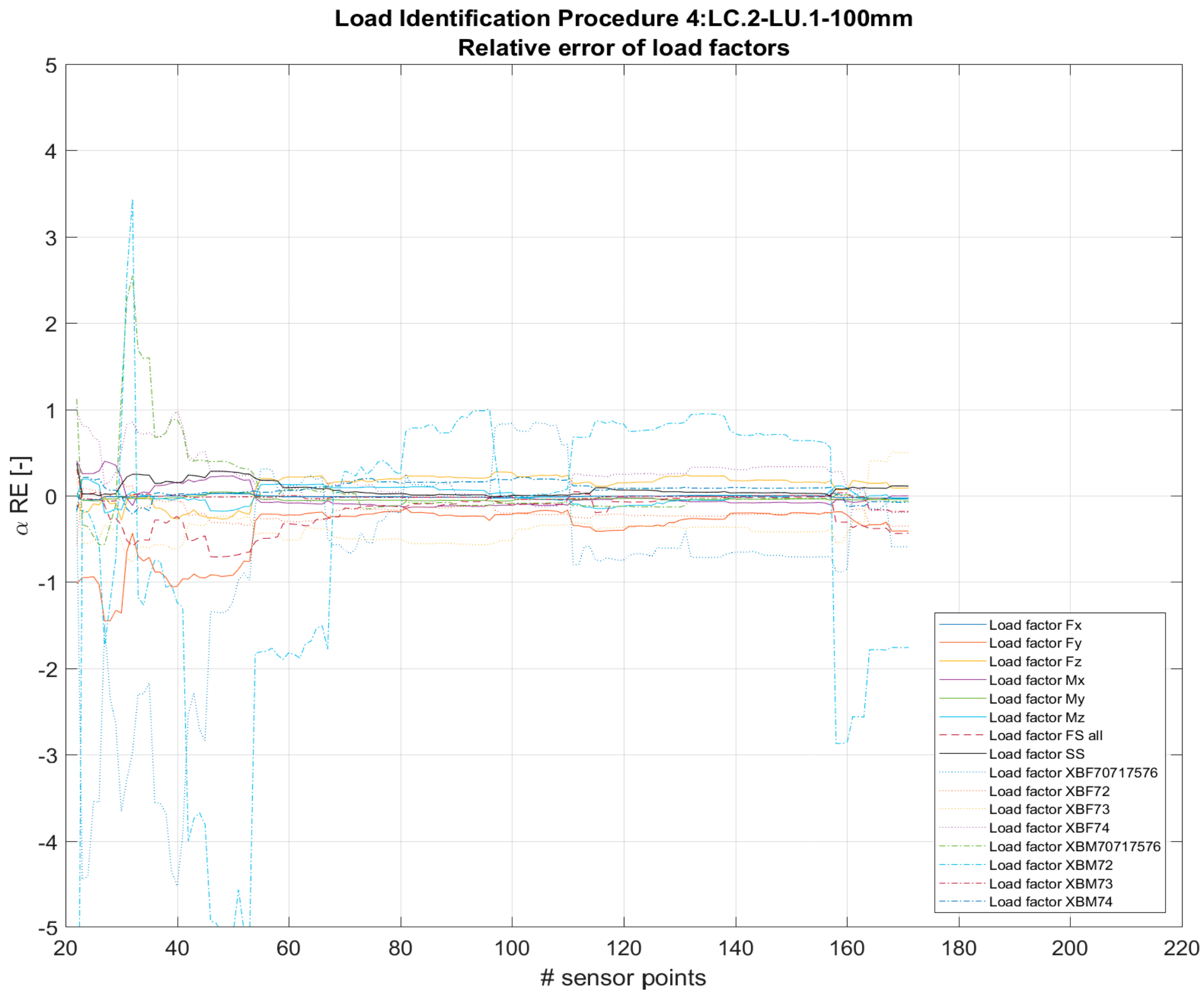

Figure 29: Load identification results of procedure 4 – LC.2 LU.1

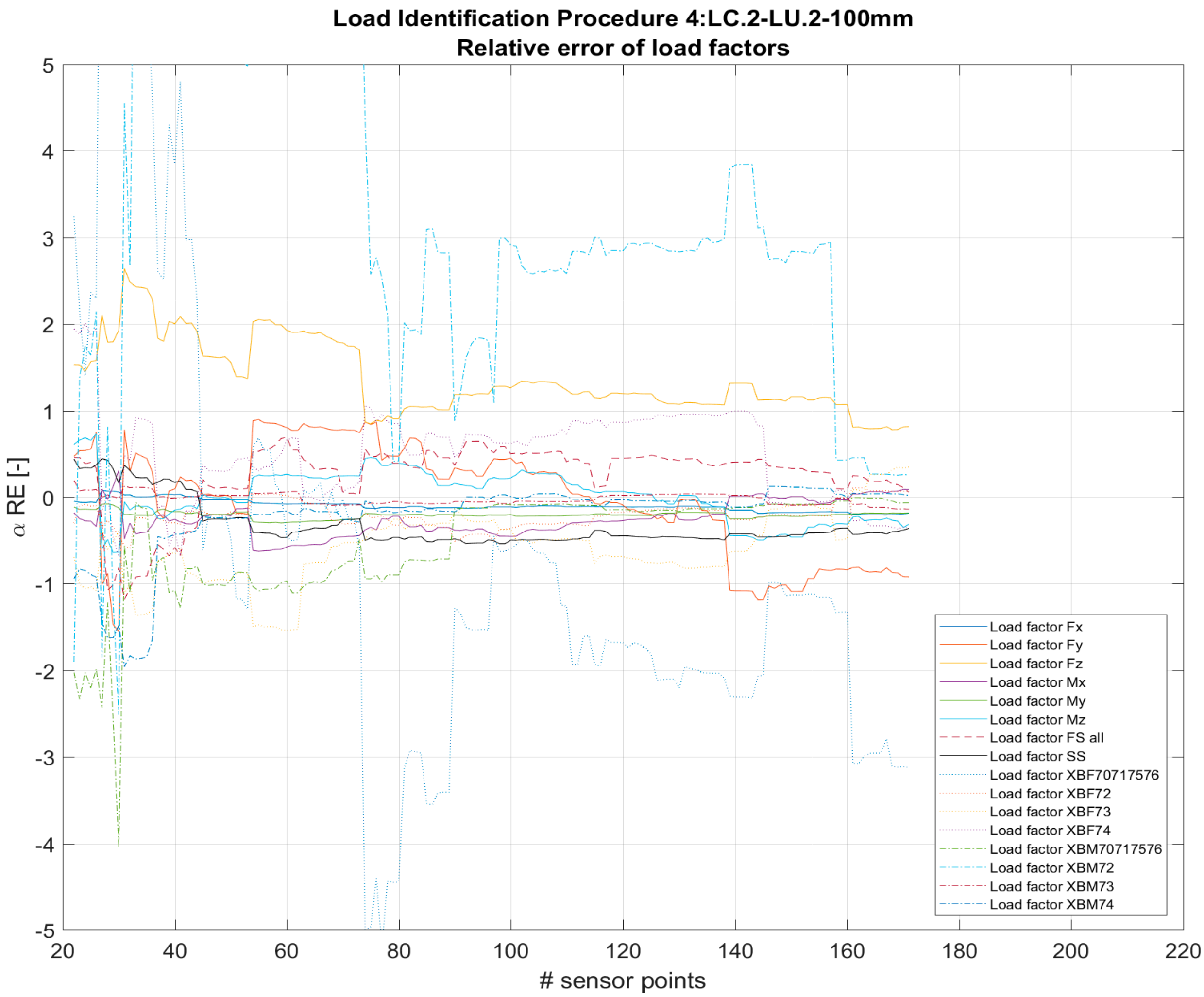

Figure 30: Load identification results of procedure 4 – LC.2 LU.2

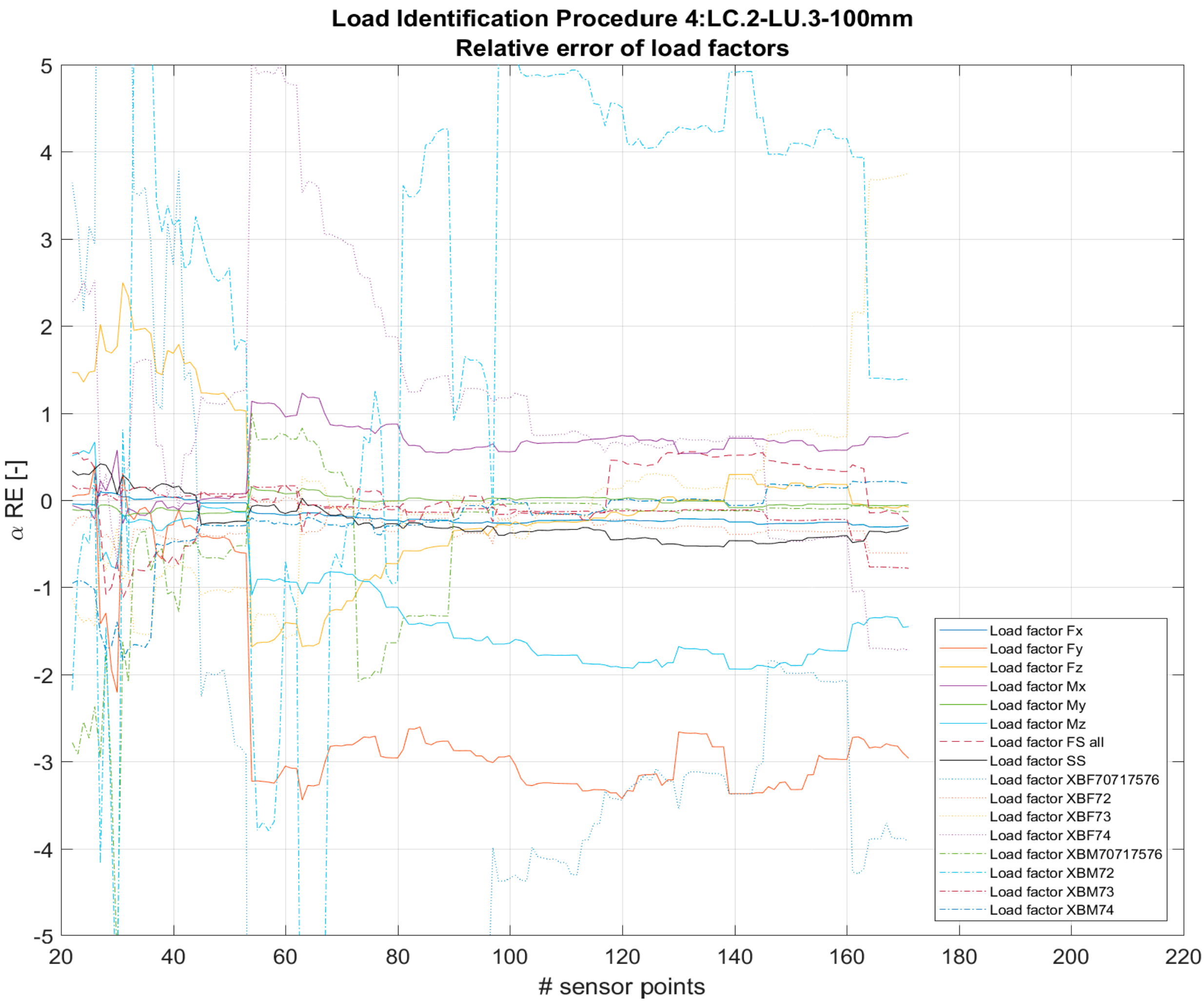

Figure 31: Load identification results of procedure 4 – LC.2 LU.3

6 Conclusion and recommendations

This paper presents the method for a load identification through a linear least squares method that determines the linear combination of these columns and results in a set of load factors. These load factors yields the best approximation of the reference strains. An efficient load determination procedure was created for complex and full scale virtual tests of large composite fuselage panels. The load identification was performed on two finite element models of fuselage panels. The first model was a simplified panel finite element model (SFEM) and the second one a highly detailed finite element model (DFEM), both created by the NLR.
The focus of the analyses laid on the strain correlation and loads identification method, the development of the efficient virtual testing modelling and analysis process and the enhancement of accurate strain extraction methods and element selection. The goal of the study was to perform a corroborate load identification on the DFEM.

The load identification of the linear analysed FE models can be performed with excellent results and thus will the reproduction of the strains field also be excellent. For the nonlinear strain field analyses the best results were achieved when the unit loads and control model were nonlinear evaluated. The two FE models deviated as the strain field reproductions of the SFEM were possible and rather good, but the strain field reproduction of the DFEM was not expectable. The error between the reference strain field and the reproduced one were too large.

There were a couple of aspects which influenced the result positive or negative. The first problem that arose was the singularity of the matrix ε_p. A high singularity in the matrix will result in poor quality of the load factors. To evaluate the singularity of the matrix the condition number can be used. Secondly, the number of significant digits in the input strains have a negative effect on the output if there are not enough digits. An effect that has a significant influence on the results is the number of sensor element used, more sensors improve the results. Also the neglecting of low strains values improved the result. This is possible due to the low impact these values have on the total strains field. Also, there was discovered that increasing the number of load creates more insecurities for the solution, but still result in fair till good results. Finally, the results are highly influenced by the choice of sensor position. If choosing the same number of sensor elements on a model spread out over the model it has a major benefit for the overall strain field reproduction as the result are improved significantly. There is demonstrated that the choice of magnitude is of influence, only there is no prove in which way

In the end the goal of reproducing a nonlinear strain field of the DFEM is not fully accomplished. Further research can be performed on the element selection. The specific placement of the sensors has major influences and advised is to look into ways to optimize the number of sensor element versus a good result.
The choice of magnitude of the unit loads should also be further investigated, as it can be of significance.

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