Combining Finite Element Analysis with Experimental Tests to Generate Accurate and Verified FE models of Scaffolding Structures

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Abstract: With the worldwide building industry constantly growing, more and more scaffolding manufacturers are entering the market. In order to assure the safety of workers, the capacity of these scaffolding systems must be accurately determined and updated with the release of new requirements.

SP Technical Research Institute of Sweden has developed methods in which Abaqus is combined with experimental test data to determine the load classification and permissible loads of scaffolding systems according to European standards.

This paper reviews the basic scaffolding components and discusses the experimental and analytical methods used to generate model input data. The paper also gives an overview of the fullscale testing and the modeling procedures that lead to verified models of scaffolding systems. The evaluation procedures are then discussed and some conclusions about how Abaqus is used in other aspects of scaffolding system development are given.

Keywords: Beam Element, Buckling, B33, Design Optimization, Experimental Verification, Failure, Flexible Joint Element, JOINTC, Nonlinear, Scaffolding, Safety, SPRINGA, Spring Element

1. Introduction

With the worldwide building industry constantly growing, more and more scaffolding manufacturers are entering the market. In order to assure the safety of workers, the capacity of these scaffolding systems must be accurately determined and updated with the release of new requirements.

The purpose of this paper is to show how Abaqus is combined with experimental test data to determine the load classification of scaffolding systems according to European standards and to allow manufacturers to quickly see the effect of potential design changes.

Component tests are performed to determine the gap, stiffness and strength of connections and components. This test data is implemented as nonlinear spring definitions. Material tests are performed on specimens extracted from actual components. This test data is converted to information for material models. An 8 meter tall by 9 meter wide section of scaffolding is vertically loaded until failure occurs while the applied load and displacements at several locations are measured. A nonlinear model of the tested system including measured imperfections is

generated and loaded until one of the components has reached its strength limit or buckling occurs. The results from the model and the test are compared to validate the model.
Finally horizontal wind loads are converted to forces that are applied to a 24 meter tall by 15 meter wide model and vertical loads are ramped until failure. The calculation results are used to determine the load classification of the system so that the safe operating limits are known. The results are also used to show the manufacturer the points of weakness so that design improvements can be made and quickly evaluated.

2. Basic scaffolding components

Scaffold systems consist of several basic components, which can be used like pieces of a large erector set to construct custom scaffolding systems for any job. At the bottom of the structure are basejacks. Each basejack consists of a baseplate, a threaded rod and a wingnut. When a scaffolding structure is built, the basejack is adjusted so that the structure can be aligned properly on uneven terrain.

The main vertical components are called standards. These standards typically range from 0.25 meters to 3 meters in length. At the top of each standard is a spigot, which is typically around 150 mm long and has a smaller outer diameter than the inner diameter of the standard so that the spigot can be inserted into the standard that rests on top of it. These standards can be stacked until the desired height of the structure is reached. The threaded rod of the basejack has a section where the nut cannot pass (at least 150 mm) so that the threaded rod can be inserted directly into the first standard. In some systems, there is a short component between the basejack and the standard called a socket that is used so that the first horizontal connection point occurs slightly below the bottom of the first standard.

The scaffold also consists of horizontal components that are attached at various heights of the scaffolding structures between the standards. The horizontal components that are aligned in the direction perpendicular to the building's facade are called transoms, and the horizontal components that are aligned in the direction parallel to the building's facade are called ledgers. There are many different designs for how the horizontal components attach to the standard. Figure 1 shows an example of one type of design. Several of the basic scaffolding components are also labeled in Figure 1.

There are also horizontal diagonals that attach in the horizontal plane between standards that are diagonally opposite each other. The horizontal diagonals contribute to the shear stiffness in the horizontal plane.

Vertical diagonals are attached at different heights on the two standards that are next to each other in the structure. The vertical diagonals contribute to the shear stiffness for the outer vertical section. Both the horizontal diagonals and the vertical diagonals are used in just selected sections of the structure. There are many ways in which both the horizontal and vertical diagonals can attach to the structure.

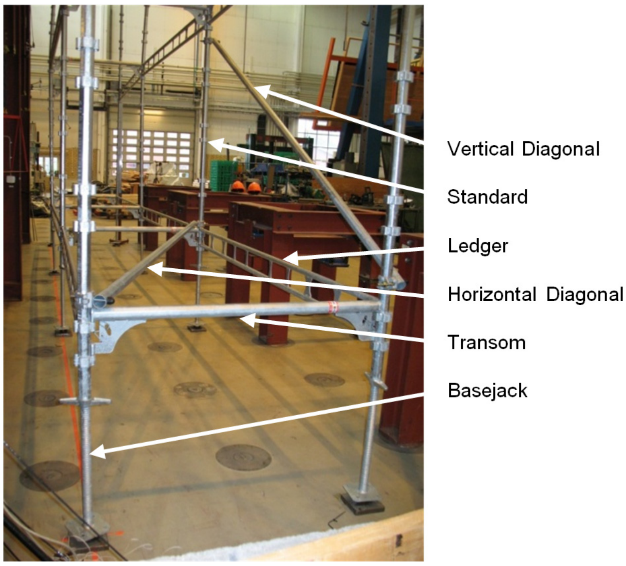

Figure 1. Basic scaffolding components.

The structure also consists of platforms, which are attached at specific horizontal levels so that workers can walk along the scaffolding. Many different platform designs and ways of attaching platforms to horizontals exist even within a single system. The different platforms are used for different types of jobs, where different loads are expected. There are also guardrails that ensure that the workers do not accidentally fall off of the scaffolding, toeboards that are attached near the platform level to reduce the risk of objects falling from the structure and stairs which allow the different levels of the scaffolding to be accessed.

The European standards outline some limitations to how the components are to be designed, but in general each manufacturer designs their scaffolding systems with different ways of connecting the components, different nominal dimensions, and different nominal material qualities. These variations are enough to make it necessary that each scaffolding system requires its own series of tests and calculations before it can receive a certification.

3. Model input data

3.1 Model input data from component tests

Component tests are performed to determine the gap, stiffness and strength of connections and components. This test data is later implemented in Abaqus models as spring (SPRINGA) elements with nonlinear spring definitions to represent the vertical and horizontal diagonal components and flexible joint (JOINTC) elements with nonlinear spring definitions to represent the connections.

3.1.1 Standard to horizontal connection

The first connection that is tested is the standard to horizontal connection. Depending on the design, there could be a different number of tests required. The following different directions, which are shown in Figure 2, must be evaluated in order to get a complete description of that connection: N, V_y , V_z, M_x, M_y and M_z.

Because the joint behaves differently for the M_y when loaded in the upwards and the downwards direction, both tests have to be run. In Abaqus, this connection is modeled as a JOINTC elements where all six of the degrees of freedom are specified. Tests in five directions lead to five nonlinear spring definitions to represent the connection. Typically the moment M_x is not tested and a linear spring with a relatively high stiffness is used for that degree of freedom. This assumption is reasonable because the stiffness in x-rotation direction for most connection types is very high and the loads in the x-rotation direction are typically low.

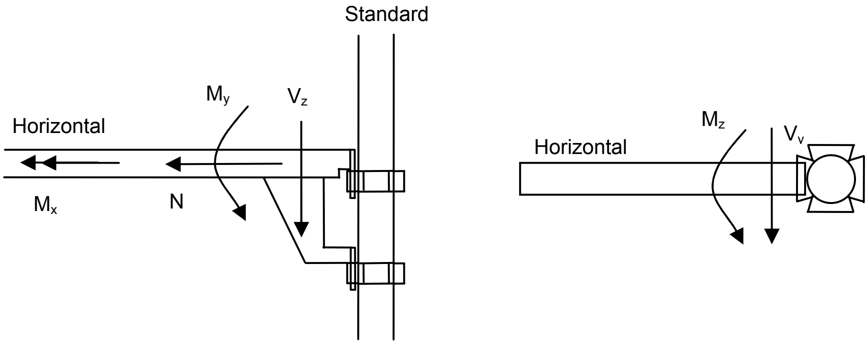

Figure 2. Test directions for the standard horizontal connection.

3.1.2 Horizontal diagonal and vertical diagonal

Characteristics of the horizontal diagonal and vertical diagonal components are also determined from component tests. These components are tested in compression, which is their weakest direction due to buckling of the tube. Nonlinear stiffnesses (including the gap) are determined from the tests and conservatively used in both the compression and tension direction. In Abaqus, the horizontal diagonals and vertical diagonals are modeled as SPRINGA elements.

3.1.3 Component test procedure

In general, the component tests all follow a similar procedure to determine the characteristics of the connections or components. The first step is to perform a pre-test. The pre-test is used to ensure that the test rig is behaving as it should, that the data acquisition system is functioning and to determine a characteristic strength that can be used in determining the cycling levels. During the pre-test, typically a low load is cycled from the positive to the negative direction several times followed by an increase in load until failure of the component with some unloadings at increasing loads. The characteristic strength (F_k) is the maximum load that the connection or component achieves before failure. Equations 1 and 2 are used to determine the low (F_{low}) and high (F_{high}) level cycling loads respectively, where γ_M is the partial safety factor for resistance and is typically equal to 1.1 and γ_F is the partial safety factor for actions, which is equal to 1.5 for permanent and variable loads:

$$F_{low} = 0.10 \times \frac{F_k}{\gamma_M \times \gamma_F} \quad (1)$$

$$F_{high} = 0.75 \times \frac{F_k}{\gamma_M \times \gamma_F} \quad (2)$$

Five tests are then run and the loads and displacements recorded at a sampling frequency of 10 Hz. Each test consists of the following steps:

- Cycle three times (in the positive and negative direction) at the low cycling load level
- Cycle three times (in the positive and negative direction) at the high cycling load level
- Increase the load until failure with at least three unloading steps at increasing loads
- Write down the type of failure and take pictures of the failure
- Take a material test specimen from the part that failed away from the stressed location

Having five sets of test data gives us a statistically significant sample size that can be used to determine design strengths. While the transducers used in the tests provide outputs of force and displacement, by recording the locations of the transducers, this force and displacement data can be converted into moment and rotation data where necessary.

3.1.4 Material tests

After the component tests are performed, the material specimens that were removed from the failed components are machined to standard material test sample geometries. This geometry depends primarily on the thickness of the material that is to be tested. The yield strength, tensile strength and percent elongation are measured and average values are determined for each component. This material information is used in the evaluation of the component tests and also in the Abaqus model of the fullscale test.

3.1.5 Evaluation of component tests

The component tests are then evaluated to determine stiffness and strength information for the different connections and components. One goal of the evaluation is to determine a mean moment versus rotation or force versus displacement curve from the tests that can be input into an Abaqus spring definition for the fullscale model. The first step is to determine the geometric looseness in the connection for each test. The geometric looseness is found by determining where the joint starts to take load at the low level cycling load. A plot of typical low level cycling data for a M_y test is shown as Figure 3.

In the figure, the red line shows where the joint begins to take load in the third negative loading cycle and the green line shows where the joint begins to take load in the third positive loading cycle. The difference between the two x-axis intersections of those lines is the geometric gap.

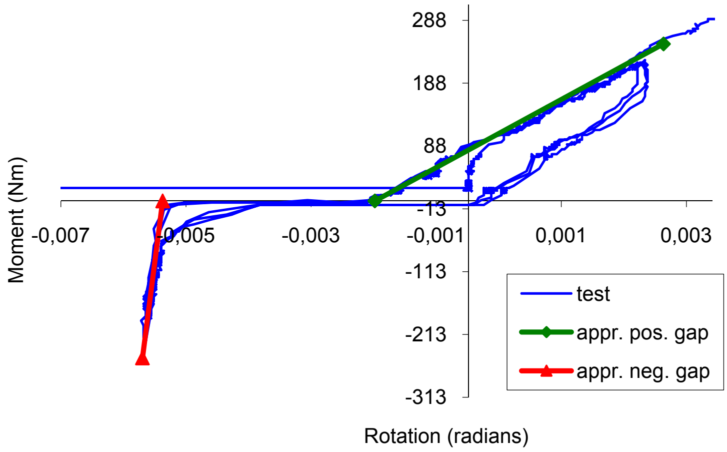

Figure 3. Plot of low cycling test data and geometric gap.

The second step is to determine approximation curves for each of the tests. Around 10 data points are used for each approximation. Figure 4 shows typical data from an M_y down test and its associated approximation curve.

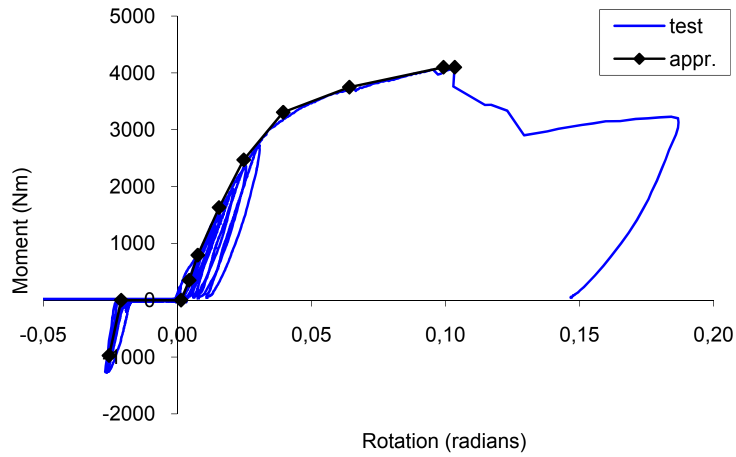

Figure 4. Plot of test data and approximation.

By generating approximation curves at the same load levels for all of the tests, the stiffness between the data point can be averaged and an average stiffness curve for the component or connection is determined. A mean strength from the tests is also calculated. By using the average geometric gap, stiffness and strength from the tests, the mean curve of the joint moment versus rotation or force versus displacement is generated. This mean curve is used to represent a relatively new part that has not been loaded past the yield strength. These mean curves are generated for each joint direction and component and are later used to verify the results of the fullscale test.

Another goal of the evaluation is to determine a design curve to represent the stiffness from each component test. The design curve is meant to show what the stiffness of the joint or component will be after the parts have been used for a significant amount of time and have been loaded past their yield strength with some additional factors of safety applied. The design curves for all joint directions and components are used in the evaluation model to ensure that the results are conservative for the entire lifetime of the scaffolding components.

The design gap is determined by calculating the gap using the same procedure as was described for the geometric gap except it is performed at the high cycling load level.

To determine the design strength from the tests, the following steps are performed:

- Reduce the strength from each test based on the material overcapacity of the tested parts
- Perform a statistical evaluation so that calculated design strength is defined as the 5% quantile for a confidence level of 75%
- Perform an evaluation of the level of ductility of the failures to determine an average partial safety factor (γ_{R2}) and reduce the strength by that factor
- Reduce the strength by γ_M

By using the design gap, average stiffness and design strength from the tests, the design curve of the joint moment versus rotation or force versus displacement is generated. Figure 5 shows plots of the approximation curves for all five tests along with the mean and design curves for a typical M_y series of tests. Note that the gap for the mean and design curve is centered around the zero rotation point. Because having no stiffness in the connections in the gap leads to convergence difficulties, a minimal level of stiffness is defined in the gaps in the models to ensure that a converged solution is reached.

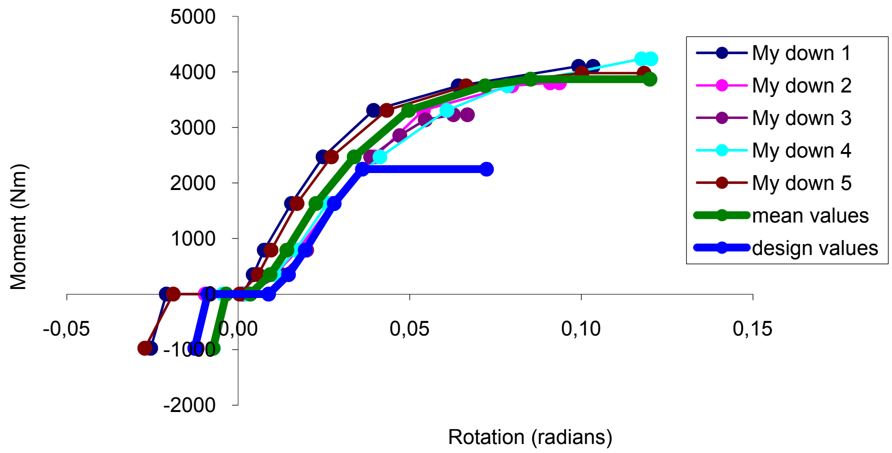

Figure 5. Plots of approximation curves, mean curve and design curve.

3.2 Model input data from calculated joints

The joint stiffness and strength between the vertical components are determined analytically. Depending on the design of the scaffolding system, the possible joints that need to be calculated between the vertical components are the basejack to socket, basejack to standard, socket to standard and the standard to standard. In Abaqus, these connections are represented as JOINTC elements where all six of the degrees of freedom are specified. The translation stiffnesses are linear and very stiff to ensure that no translation at those joints takes place. The rotation stiffness around the axis of the vertical member is linear and set to a low value that is meant to approximate friction. The stiffnesses in the other two rotation directions are specified using identical nonlinear spring definitions. Like the other joints, there are two different curve definitions that are used for the models. The first is the mean curve which takes into account the calculated stiffness and mean strength and the second is the design curve which uses the same stiffness but with the design strength as the maximum allowable load.

The nominal dimensions of the components are used to determine a geometric gap, which describes how far the joint can rotate before load is taken in the joint. This is based on the difference in the diameters of the components and the length of the overlap between the two components that are connected at that point. The geometric gap is used for both the mean and design curves. The stiffness is a function of the material type and the dimensions of the components that are connected at the joint. The mean strength is determined by the geometry of the parts and the nominal yield strength and the design strength is determined using the design yield strength. For the connections involving the basejacks, the section properties of the thread have been simplified according to the SS-EN 12811-1 standard to an equivalent thickness and plastic modulus.

4. Fullscale test

In order to ensure that the modeling technique functions correctly for the scaffolding system, a fullscale test is performed and a model of the tested configuration is generated. The tested scaffold is typically erected with 3 sections and 4 platform levels to a total height of around 8 m (see Figure 6). The section length and the distance between the standards in the direction perpendicular to the facade can vary depending on the scaffolding structure to be tested but the height between platform levels is usually 2.0 m. The test structure is typically erected without platforms, guardrail frames or toeboards.

The basejacks are adjusted to their maximum height and are placed on a flexible ball joints on a concrete floor. The basejacks are placed on the flexible ball joints to ensure that the boundary conditions are known for the verification model.

Wall anchors are mounted every 4 m with double anchorages at the left hand of the scaffold. Pinned connections are used for the single anchors so that the boundary conditions are known for the verification model.

Horizontal and vertical diagonals are typically placed in the left section from the bottom to the top of the scaffold.

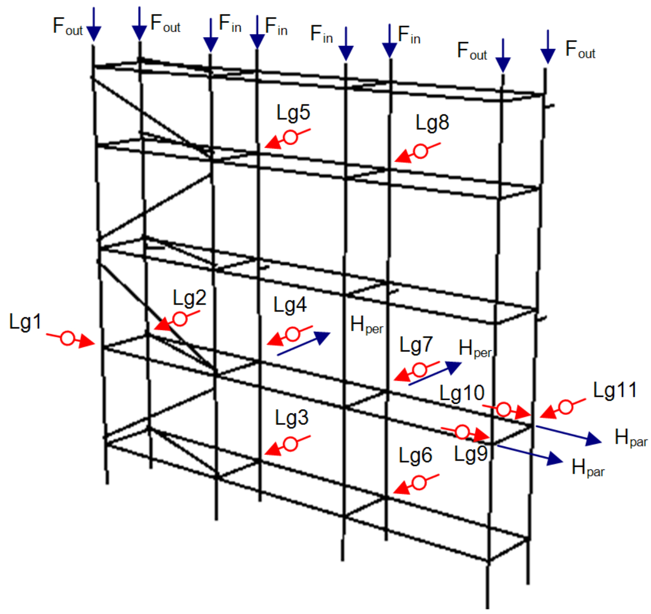

Figure 6. Fullscale test model with instrumentation from the fullscale test labeled.

Around 10 displacement gauges are used to measure the horizontal movements of the scaffold during loading. A typical test setup consists of eight gauges perpendicular to the facade and three gauges parallel to the facade, see Figure 6.

Because the vertical components are not perfectly straight, the inclination of the vertical components is measured before the loads are applied.

Horizontal loads in the direction perpendicular to the facade (H_{per}) and the direction parallel to the facade (H_{par}) are first applied to ensure that the looseness of the joints is activated. The vertical loads F_{out} and F_{in} are then increased progressively until failure occurs. The ratio between the vertical loads on the outer standards (F_{out}) and the vertical loads on the inner standards (F_{in}) is kept to 1:2 during the entire loading. During the application of the load, the loads and displacements are measured with a sampling frequency of 1 Hz.

5. Fullscale model

5.1 Geometry, boundary conditions and input data of components

A model of the tested system (see Figure 6) including measured imperfections is generated in an input file. The fullscale model uses 2-node cubic beam (B33) elements to represent the tubular components of the scaffold with the beam sections determined from nominal dimensions. The characteristic material models include plasticity, where the data has been obtained from material tests performed at SP or from nominal material properties provided by the manufacturer. For aluminium scaffolds, the heat affected zones around welded features are modeled with reduced material strengths. The size of the heat affected zone is determined based on the type of welding used to produce the components. The JOINTC and SPRINGA elements are represented using the mean curves from the component tests and calculations because they do not have factors of safety applied and should therefore most closely match reality.

5.2 Loads

The self weight is applied in a static general step by converting the masses of the components into forces that are applied throughout the structure as concentrated forces and line loads. The next step is a static Riks step in which the horizontal and vertical loads are applied until one of the components has reached its mean strength or buckling occurs in one of the vertical components. The nonlinear effects of large deformations and displacements are included in the calculation.

5.3 Results

The results from the model and the test are compared to ensure that the maximum achieved load and displacements match the test data closely. Because of imperfections in the structure, the joints do not actually start in the middle of the gaps. With that in mind, if there are some discrepancies between the initial calculations and the test results, the gaps in the joints can be adjusted within reasonable limits until displacements and the final load match the test results. If there continues to be discrepancies between the model and the test results, the cross sectional dimensions of the tested components can be measured and the beam sections can also be adjusted. When the results from the model conservatively match the failure load and stiffness of the structure within 5-10%, the calculation method is considered verified. Three comparison plots from a verified model are shown as Figure 7. Also, a picture of a scaffolding system at failure along with the corresponding model at failure is shown in Figure 8. Once the fullscale model is verified, we can be sure that the modeling technique is acceptable for the scaffolding system and the larger evaluation model can be generated.

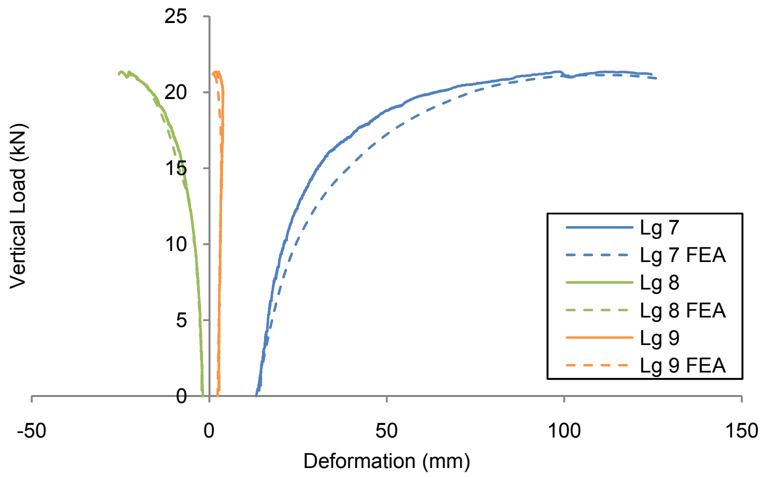

Figure 7. Comparison plot from fullscale test and model.

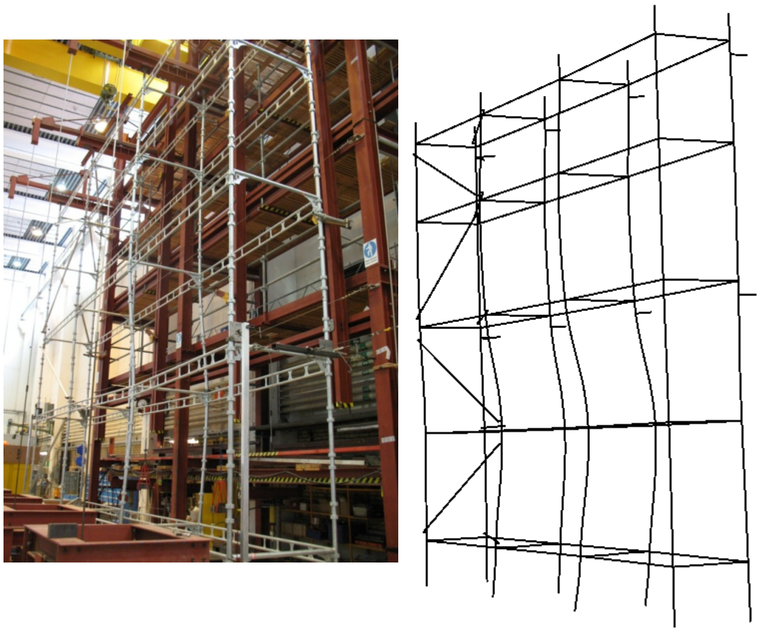

Figure 8. Picture of the fullscale test failure and associated model results.

6. Evaluation model

6.1 Geometry, boundary conditions and input data of components

An example of the geometry of the numerical model used in the evaluation of the scaffolding system load classification is shown in Figure 9. The modeled structure is around 24 m high and consists of 5 sections. The section length and the distance between the standards in the direction perpendicular to the facade can vary depending on the scaffolding structure to be evaluated, but the height between platform levels is typically 2.0 m. The beam sections are determined from the nominal dimensions. The material models again include plasticity, but instead of characteristic material properties, design values of the material properties are used. For aluminum scaffolding components, the reduced material strengths in the heat affected zones around welds are again taken into account. The JOINTC and SPRINGA elements are represented using the design stiffnesses and design strengths from the component tests and calculations. This is because the evaluation model is used to represent a scaffold that has potentially been loaded past its yield strength and it has safety factors applied to ensure that the model is conservative throughout the lifetime of the scaffolding components. The full design gap is used for all joints except the connection between the basejacks and the rest of the structure. This is because the supports of the basejacks are modeled with the maximum possible inclination in the direction perpendicular or parallel to the facade (depending on the wind direction).

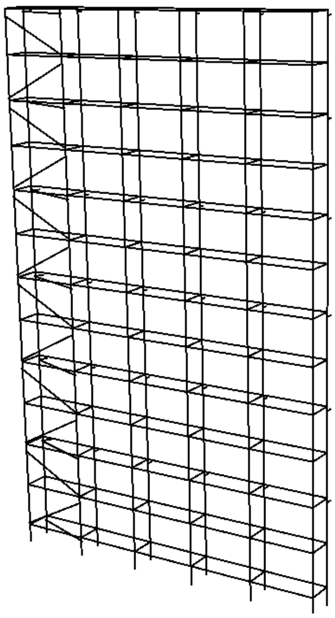

Figure 9. Evaluation model.

The points of support of the base jacks were modeled as JOINTC elements, where the spring definition is specified in the SS-EN 12811-1 standard and is a function of the failure load of the structure and the geometry of the basejack. The tie members are pinned to the facade and able to transmit forces perpendicular and parallel to the facade only.

6.2 Loads

The structure is verified for two wind conditions in the direction perpendicular and parallel to the facade respectively. For each load condition, different combinations of loads were developed according to the following:

- The service condition
    - Self weight of the scaffold
    - 1.5 times the uniformly distributed service load
    - Working wind load 200 N/m²
- The out of service condition
    - Self weight of the scaffold
    - 50 % of the uniformly distributed service load (load class 4)
    - 25 % of the uniformly distributed service load (load class 3)
    - Maximum wind load 560 - 770 N/m²

The areas of the components that would be contacted by the wind are determined and equivalent forces to represent the wind load on the structure are calculated. Increasing wind loads due to piles of material for both load cases is also considered.

The vertical loads are a function of the load class of the scaffolding system and the load case that is run. For the service condition, the loads are meant to represent materials and workers present on the scaffolding. For the out of service condition, the loads are representative of material left on the scaffold in a storm.

In the model, the self weight is applied in a static general step by converting the masses of the components into forces that are applied throughout the structure as concentrated forces and line loads. While the stiffness associated with guardrail frames, platforms and toeboards is not included in the evaluation model, additional concentrated forces to simulate the weight of these components are added to the model. The horizontal wind loads are also applied in a static general step. The next step is a static Riks step in which the vertical loads are applied until one of the components has reached its design strength or buckling occurs in one of the vertical components. The nonlinear effects of large deformations and displacements are included in the calculation.

Because the spring definition of the point of support for the basejack is dependent on the failure load of the structure, several iterations must be run where the spring definition is updated.

6.3 Evaluation

The static Riks method allows the user to see the maximum load that the structure holds before the entire structure fails. However, the static Riks method makes it possible to follow the redistribution of loads, which means that the maximum applied load on the structure is often higher than the applied load when a single component fails. Because the desired output is the maximum applied load before a single component fails, the output must be reviewed closely and the load in which the first component fails must be determined. Different components have different criteria for failure. The ratio of ultimate capacity (I) takes the interaction of bending section moments and section force into consideration. A value of $I \geq 1.0$ means that the element can not resist any more load.

Steel components that are simplified as tubes of uniform thickness, such as the horizontals, standards, sockets and basejacks are evaluated with following interaction equations, where $M_{N,Rd}$ is the reduced design value of the resistance to bending moments making allowance for the presence of normal forces:

$$M_{N,Rd} = 1.04 M_d \left(1 - \left(\frac{N}{N_d} \right)^{1.7} \right), \qquad M_{N,Rd} \leq M_d \tag{3}$$

$$I = \left(\frac{M_1}{M_{N,Rd}} \right)^2 + \left(\frac{M_2}{M_{N,Rd}} \right)^2 \tag{4}$$

The design moment (M_d) and normal force (N_d) for each component is calculated based on the component's cross section. The cross section must first be classified according to the EN 1993-1-1 standard to determine how much of the cross section can yield before failure of the cross section occurs. The plastic modulus of the cross section and the area along with the design material properties are used to determine M_d and N_d. For the threaded section of the basejacks, the methods described in SS-EN 12811-1 are used to determine the design resistances. M_1, M_2 and N are the actual moments and normal forces in the elements. While slightly different interaction equations are used for aluminium components, the procedure is the very similar.

Horizontal and vertical diagonals are evaluated with following equation:

$$I = \frac{N}{N_d} \tag{5}$$

A linear interaction between the M_y moment, N and the shear forces V_z and V_y is used for the connection between the standard and horizontal. The design strengths are determined as discussed in section 3.1.

$$I = \frac{M_y}{M_{y,d}} + \frac{N}{N_d} + \frac{V_z}{V_{z,d}} + \frac{V_y}{V_{y,d}} \tag{6}$$

A python script that reads the output database file was written so that the design strengths for all components are input and a field output variable that contains the interaction values for each component for each increment is generated. This enables the maximum interaction for all components to be viewed as a contour plot, which allows the user to quickly see which component fails first and at which increment the failure occurs.

6.4 Results

By reviewing the output of the python script, the average vertical load in the pair of standards where the first failure occurs is determined for each of the four load cases. The vertical loads are compared to the dimensioning service load for the different load classes and a load class for the scaffolding structure is determined.

Additionally, the minimum average standard load at failure is divided by γ_M to determine a permissible standard load that can be used by the manufacturer to ensure safe design of other scaffolding configurations.

7. Conclusions

The procedure to determine the load classification and permissible standard load for scaffolding systems relies on both extensive experimental test data and a powerful finite element tool such as Abaqus to be able to model the scaffold as close to reality as possible. The procedure presented herein leads to verified models of scaffolding structures that allows for load classifications of these structures to be determined and ultimately keeps workers safe.

Once an evaluation model has been generated for a scaffolding system, the manufacturer can quickly learn a number of important things about the system. Maximum permissible heights of the system can be easily calculated. The effect of adding components such as a stair tower to the structure can also be observed. The model can even be used to see the effect of changes to the configuration of the system. Examples of this are shorter basejacks, changes to materials properties of components, changes to cross sections, changes to the type of platforms to be used and changes in the length of standards to be used. The model is often used to highlight points of weakness in the structure that the manufacturer can improve to achieve even higher load classifications or permissible standard loads.

This same procedure can be used for other application as well. One such application is the evaluation of grandstands that also use scaffolding components.

In addition to checking the load classification of the entire structure, Abaqus is used in scaffolding projects to develop detailed solid element models of individual components which are used for load classification of individual components and for design optimization.

In this way Abaqus is helping to shape the future of scaffolding design and ensuring better working environments and safety for people all over the world.

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Acknowledgments

The authors would like to thank the lab technicians of the Building Technology and Mechanics department at SP Technical Research Institute of Sweden for their hard work and dedication to providing accurate and well documented results.

We would also like to thank HAKI AB for allowing us to use pictures and sample data from tests of their Universal Light scaffold system in this paper.