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REDUCING COST IN JACKET DESIGN: COMPARING THE INTEGRATED AND SUPERELEMENT APPROACH

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ABSTRACT

Lowering the cost of energy is one of the main focus areas of the offshore wind industry. Moving into deeper waters, support structures have become more complex and jacket foundations have become more common. Ideally an integrated design of jacket and wind turbine in an aero-elastic simulation code is performed resulting in the most optimized and cost-efficient design. An alternative option is to use a superelement reduction of the jacket model before importing into the aero-elastic tool for dynamic analysis. This approach also has the advantage of a clear division in responsibility between the foundation designer and wind turbine designer and protects intellectual property. In this paper, integrated and superelement modelling approaches are carried out for a wind turbine on a jacket support structure, using combined workflows in Bladed and Sesam. It is shown that the results of integrated and superelement simulations match closely for both fatigue and extreme environmental and operating conditions, in terms of structural loading and dynamic response. The interfaces between Sesam and Bladed have been verified, giving confidence in the model conversion and data exchange between the packages. This means that instead of using a single tool for the analysis, it is now possible to use well-interfaced tools like Sesam and Bladed in a superelement workflow, without significant loss of modelling fidelity compared to an integrated approach, and without risk of introducing errors during the design approach. Such well-interfaced tools allow for greater design optimisation with the ultimate aim of lowering the cost of energy.

1. INTRODUCTION

Lowering the cost of energy is one of the main focus areas of the offshore wind industry. Moving into deeper waters, support structures have become more complex and jacket foundations have become more common. Ideally an integrated design of jacket and wind turbine is performed resulting in the most optimized and cost-efficient design [1]. However, due to intellectual property rights, expertise in only one of the two competence areas and/or division of responsibilities, this is not always possible.

In integrated design, a single tool is used to calculate wind and wave loads on the turbine and foundation, enabling the twin benefits of i) a more optimized design process with a single set of combined wind and wave load calculations, and ii) removing potential quality issues of data conversion between codes. Since this is not always possible in industry, the next best option is to use a method with well-integrated tools.

One such method is to use a superelement approach [2], which involves reducing the full jacket design into a set of structural matrices describing the foundation’s response at the interface with the turbine tower. This allows a foundation designer to model the structure in their desired software, while the turbine manufacturer can include the superelement matrices in their load calculations. This removes the need to remodel the complete foundation and lowers the risk of errors. This allows for a smoother data exchange and verification process.

In this paper, a superelement approach and an integrated approach are compared. The comparison focuses on the loading and kinematic predictions of each approach, and explores the benefits and disadvantages of each method.

2. METHOD

Two industry leading software packages are used in this study; offshore structure strength assessment software Sesam and wind turbine aero-elastic software Bladed.

2.1 WORKFLOWS

Sesam and Bladed can support the integrated and superelement analysis workflows.

The methods are described here and visualized in Figure 1.

2.1 (a) Integrated analysis

The modelling of the jacket and tower is done in Sesam. The model is then converted into Bladed format and linked to a wind turbine model in Bladed. A combined wind and wave loads analysis is then performed in Bladed, after which the resulting forces and moments are extracted for every beam in the structure. These results are then converted into Sesam format. Fatigue and extreme analysis is subsequently performed in Sesam.

2.1 (b) Superelement analysis

The modelling of the jacket is done in Sesam. The model and wave loads are then reduced into a superelement using a Craig-Bampton method [3], and linked to a wind turbine and tower model in Bladed. A structural analysis including wind on the turbine and wave loads from the Sesam superelement is then performed in Bladed, after which the forces and moments are extracted at the interface point. These loads are then applied to the model in Sesam, together with the original wave loads, and the structural analysis is run. Fatigue and extreme analysis is subsequently performed in Sesam.

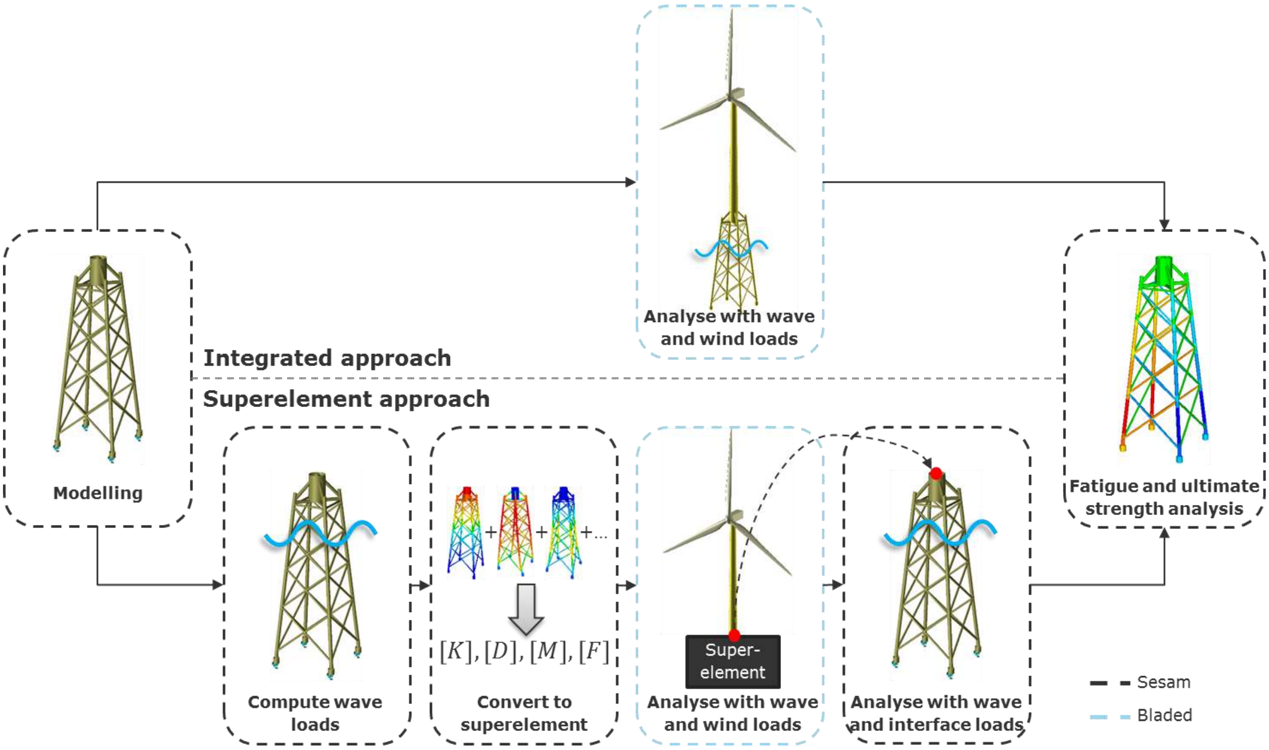

Figure 1: Visualization of the integrated and superelement workflows.

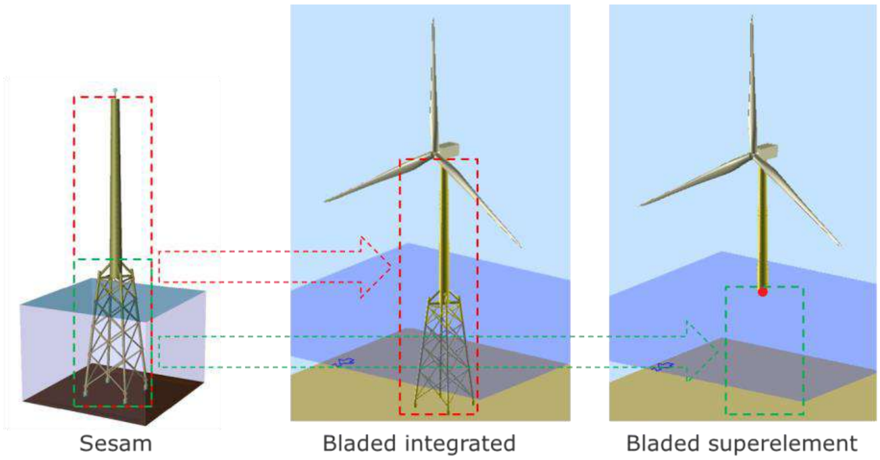

Figure 2: Left: complete structure including jacket and tower and point mass RNA in Sesam. Middle: jacket and tower from Sesam combined with wind turbine in Bladed. Right: superelement from Sesam combined with wind turbine in Bladed.

2.2 MODELS

The verification study is based on a jacket with a 7MW generic wind turbine on top. The turbine assumed for the jacket has a rotor nacelle assembly (RNA) mass of 410 tonnes, rotor diameter of 154 m and hub height at 105 m. The following models are used in the verification study (see also Figure 2):

- **Bladed integrated**: Sesam jacket and tower structure converted into Bladed format. Support structure gravity and wave loads are generated in Bladed. RNA is added in Bladed.
- **Bladed superelement**: Sesam jacket structure converted into a superelement for Bladed. Gravity and wave loads on the jacket generated in Sesam. Tower and RNA are added in Bladed.
- **Sesam re-tracking**: Re-creation run in Sesam. Jacket model defined in Sesam. Interface loads from Bladed superelement runs are applied to the jacket top. Wave loads and gravity applied to the jacket by Sesam.
- **Sesam 'integrated'**: Jacket structure, tower and point mass RNA. Only used for initial frequency comparisons without the wind turbine.

To compare the different analysis types in Sesam and Bladed properly, it was required to align modelling settings in many areas including: beam eccentricities, geometric stiffening, structural damping, granularity of applied hydrodynamic loads, Wheeler stretching, and Morison coefficients. Full details are presented in [4].

2.3 LOAD CASE SETUP

The legs were flooded and Morison coefficients assigned to the jacket. No marine growth was assigned.

Some simulations were run using fatigue conditions of wave and wind loading, while others used extreme load conditions. These are described in Table 1 and Table 2 respectively. Additional wave types (such as a constrained wave) were also run, but are omitted here for brevity. The reader is referred to [4] for further details.

The irregular Airy wave sea surface was generated in Bladed and Sesam using superposition of identical sine wave components. This ensures that the sea surface matches exactly in Bladed and Sesam.

The time domain analysis is run for 630 seconds (with the first 30 seconds being discarded due to potential start-up transients), with a time step of 0.1s for the wave load generation. In both Sesam and Bladed, the results output time step was 0.05s. An internal calculation time step for the structural analysis of 0.025s is used in Sesam, while the coupled analysis time step in Bladed was 0.01s.

Table 1: Fatigue load case description

Parameter	Value
Wave type	Irregular
Significant wave height	4.6 m
Zero-upcrossing period	6.52 s
Peak period	8.6 s
Peak enhancement factor	3.1
Current	None
Wave theory	Airy
Wind field	3D turbulent
Mean wind speed	20 m/s
Wind turbine state	Operating, power production

Table 2: Extreme load case description

Parameter	Value
Wave type	Regular
Significant wave height	Wave height: 16 m
Wave period	12.5 s
Current	1.6 m/s over whole depth
Wave theory	Stream function 8th order
Wind field	3D turbulent
Mean wind speed	50 m/s
Wind turbine state	Parked

3. VERIFYING SUPERELEMENT CONVERGENCE

Before a result comparison can be performed, a valid superelement needs to be created. Besides the format (see [5]), the superelement data itself needs to be converged to make sure that the superelement gives the same dynamic response as the original jacket, so that it can be used as a replacement of the original model. The verification requirements relate to spectral convergence and spatial convergence.

3.1 SPECTRAL CONVERGENCE

To verify spectral convergence of the superelement, the mode shapes of the superelement model are compared to the full standalone jacket model.

For the explicit model of the jacket, the eigenfrequencies were calculated accounting for added mass and internal water. For the superelement model, the number of Craig-Bampton mode shapes can be increased until the superelement eigenfrequencies match those of the explicit jacket model.

Including 40 modes in the superelement led to a maximum error in natural frequency between the full and reduced model of 0.5% for the first 20 modes (up to 10 Hz), see Table 3.

Table 3: The free interface natural frequencies of the standalone jacket

Mode	Freq. [Hz] (explicit)	Freq. [Hz] (superelement)	Diff. [%]
1	1.783	1.784	-0.06 %
2	1.783	1.784	-0.06 %
3	4.955	4.955	0.00 %
4	5.084	5.085	-0.02 %
5	5.365	5.369	-0.07 %
6	5.365	5.369	-0.07 %
7	6.177	6.177	0.00 %
8	6.425	6.425	0.00 %
9	6.592	6.592	0.00 %
10	6.945	6.980	-0.50 %
11	6.964	6.988	-0.34 %
12	6.964	6.988	-0.34 %
13	8.156	8.179	-0.28 %
14	8.156	8.179	-0.28 %
15	8.232	8.232	0.00 %
16	9.096	9.096	0.00 %
17	10.298	10.317	-0.18 %
18	10.298	10.317	-0.18 %
19	10.583	10.605	-0.21 %
20	10.936	10.936	0.00 %

3.2 SPATIAL CONVERGENCE

To verify spatial convergence selected load cases were run on the superelement model. It was verified that the displacement at the interface of the full model and superelement model were in agreement.

4. RESULT COMPARISON

As part of the verification study, the mass and mode frequencies of all models were compared. Loads and kinematics were compared at the interface as well as at some points in the jacket and at tower top.

4.1 MASS COMPARISON

The masses of the jacket and tower were found to be identical for all models in each software tool.

4.2 EIGENFREQUENCY COMPARISON

Natural frequencies were compared for the stand-alone jacket first, which gave good agreement. The same was then done for the models including jacket or superelement, tower and RNA point mass in Sesam and Bladed.

For the frequency comparison, the Sesam superelement was set up with a tower and rigid RNA mass and inertia connected to it in Sesam too, similar to how the Sesam superelement is used in Bladed.

Table 4 contains the natural frequencies of the model including jacket, tower and RNA point mass, both as a full model and as a superelement model, in both Sesam and Bladed. From the table it can be seen that there is good agreement between all models. In particular:

- There is a close match between the superelement and full model in Sesam.
- There is a close match between the full model in Bladed and Sesam.
- The superelement model in Bladed has a close match to the superelement model in Sesam.

The agreement in natural frequency provides confidence that the models are well aligned before proceeding with time domain comparisons.

Table 4: The natural frequencies of the jacket including tower and RNA point mass

Mode	Sesam 'integrated' [Hz]	Sesam SE vs Sesam 'integrated' [%]	Bladed integrated vs Sesam 'integrated' [%]	Bladed SE vs Sesam SE [%]
1	0.281	0.00 %	0.06 %	0.06 %
2	0.281	0.00 %	0.06 %	0.06 %
3	1.578	0.06 %	0.23 %	-0.03 %
4	1.578	0.06 %	0.23 %	-0.03 %
5	3.513	0.03 %	-0.07 %	-0.16 %
6	3.513	0.03 %	-0.07 %	-0.16 %
7	4.606	0.07 %	0.05 %	0.01 %
8	4.955	0.00 %	0.13 %	-0.01 %
9	5.015	0.02 %	0.47 %	0.00 %
10	5.398	0.06 %	0.10 %	-0.01 %
11	5.398	0.06 %	0.10 %	-0.01 %
12	6.180	0.00 %	0.17 %	-0.01 %
13	6.425	0.00 %	0.33 %	-0.01 %
14	6.592	0.00 %	0.09 %	0.00 %
15	6.864	0.25 %	0.08 %	-0.05 %
16	6.864	0.25 %	0.08 %	-0.05 %
17	8.018	0.09 %	0.16 %	-0.05 %
18	8.018	0.09 %	0.16 %	-0.05 %
19	8.227	0.00 %	0.11 %	0.00 %
20	9.096	0.00 %	0.05 %	0.00 %
21	9.666	0.34 %	0.30 %	0.01 %
22	9.668	0.57 %	0.50 %	0.00 %
23	9.917	0.06 %	0.16 %	-0.27 %
24	9.917	0.06 %	0.16 %	-0.27 %
25	10.501	0.36 %	0.00 %	-0.18 %
26	10.501	0.36 %	0.00 %	-0.18 %
27	10.936	0.00 %	1.95 %	0.00 %

4.3 LOADS AND KINEMATICS COMPARISONS IN TIME DOMAIN

4.3 (a) Comparison locations

Loads and kinematics are compared at the following locations in the models:

- Superelement interface node: loads, displacements, velocities, accelerations
- Tower top: displacements
- Jacket leg (Jt_K_5_4): displacements
- Jacket X-brace member (Jt_X_1_3): loads

The jacket locations are shown in Figure 3. The superelement interface loads are presented for both the FLS and ULS load cases and for all three models.

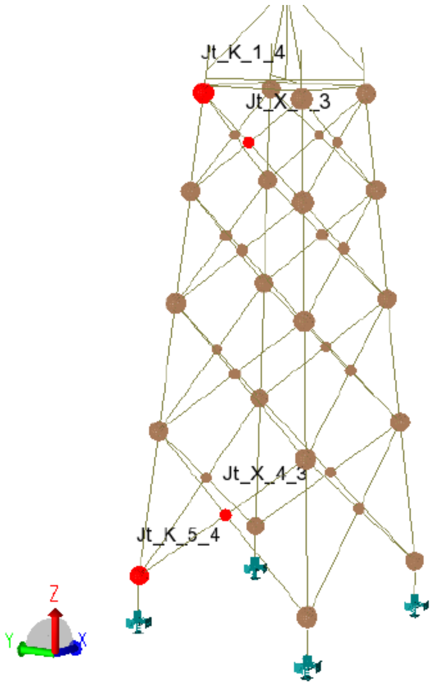

Figure 3: Selected result locations Jt_K_5_4 and Jt_X_1_3 within the jacket.

The tower top displacement is shown for the "Bladed superelement" and "Bladed integrated" runs only, as the tower top is not modelled in the "Sesam re-tracking" run.

The jacket displacements and loads are shown for the "Bladed integrated" and "Sesam re-tracking" runs only, as the jacket is not modelled explicitly in the "Bladed superelement" case.

Multiple locations have been chosen because differences in modelling, analysis or damping may be small in the jacket or at the interface, but might become more pronounced at the tower top, or vice-versa.

4.3 (b) Fatigue load case, irregular wave

The resulting loads, displacements, velocities and accelerations at the interface are shown in Figure A.1 to Figure A.4.

Tower top displacements are presented in Figure A.5.

Jacket loads are displacements are presented in Figure A.6 and Figure A.7.

An excellent match has been observed in the interface loads, interface kinematics, tower top displacement, jacket loads and jacket displacements.

This confirms the correct implementation of the superelement and loads conversion from Sesam to Bladed and vice versa for the interface loads. This also confirms that enough modes were included in the superelement used in this verification study. The integrated analysis results from Bladed match closely to the superelement results as well, which confirms that the Airy wave hydrodynamic modelling and structural modelling is well aligned in Sesam and Bladed.

4.3 (c) Extreme load case, regular wave

The resulting loads, displacements, velocities and accelerations at the interface are shown in Figure A.8 to Figure A.11.

Tower top displacements are presented in Figure A.12.

Jacket loads are displacements are presented in Figure A.13 to Figure A.14.

An excellent match has been observed in the interface loads, interface kinematics, tower top displacement, jacket loads and jacket displacements.

This shows that for large waves, the superelement assumptions are still valid and give equivalent results to the integrated modelling. It is also demonstrated that the Stream function wave hydrodynamic modelling in Bladed and Sesam is equivalent.

4.3 (d) Discussion of the results

From the presented results, it is clear that the integrated and superelement models in Sesam and Bladed match well. The results of all methods give comparable results for support structure loads and kinematics, as well as natural frequencies.

The results demonstrate that:

- The automatic conversion of a Sesam support structure model into a Bladed model is working correctly, and properly takes into account all coordinate systems and direction transformations.
- The superelement in Sesam was adequately converged before converting it into Bladed format.
- Reduction of a Sesam support structure model into superelement and load files in Bladed format has been implemented correctly in Sesam.
- The superelement and reduced wave loads are properly taken into account in the Bladed superelement analysis, and the interface loads are properly computed.
- The automatic conversion of the result files from Bladed into Sesam result files and interface load files is implemented correctly.

Given that both workflows give similar results, the question may arise which workflow to use. This depends on different factors as well as the parties involved in the project. Both methods have their own strengths, and both methods have some reasons why it should or should not be used in certain cases:

- The main benefits of the integrated design approach are that the analysis is performed on the complete structure in one go. This requires less model conversion and enables a holistic approach to design optimisation. Additionally, hydro-elastic coupling effects on wave loads due to structural deformations are considered during the analysis in Bladed. However, the support structure is limited to a beam model.
- Conversely, the superelement approach allows for a clear split of responsibility between the foundation designer and wind turbine manufacturer. The intellectual property rights remain separated in this approach, although it is noted that Bladed's encryption feature can be used to protect intellectual property in an integrated design approach. The superelement approach also allows for more complex modelling features in the structure in Sesam, such as shell models.

5. CONCLUSIONS

Integrated and superelement approaches to wind turbine support structure design have been presented using combined workflows using Bladed and Sesam.

The results of the two methods give comparable results for support structure loads and kinematics, as well as natural frequencies. The superelement linear assumptions remained valid even in the case of extreme environmental conditions.

Well-interfaced tools such as Bladed and Sesam enable efficient model conversion and data exchange in both superelement and integrated modelling approaches. These robust interfaces can save time and reduce errors in the design process, leading to design improvements and reduction in cost of energy.

Deciding which workflow to choose typically depends not only on technical factors, but also on matters such as intellectual property rights, competence areas and/or division of responsibilities of the parties are involved.

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4. L.M. Alblas and W. Collier, 2017 'Verification report of Sesam's Bladed interface (report no. 2016-0866)', *DNV GL, Høvik, Norway*
5. W. Collier, 2016 'Superelement User Guide for Bladed', *DNV GL, Bristol, UK*

APPENDIX A COMPARISON PLOTS

A.1 FATIGUE LOAD CASE, IRREGULAR WAVE

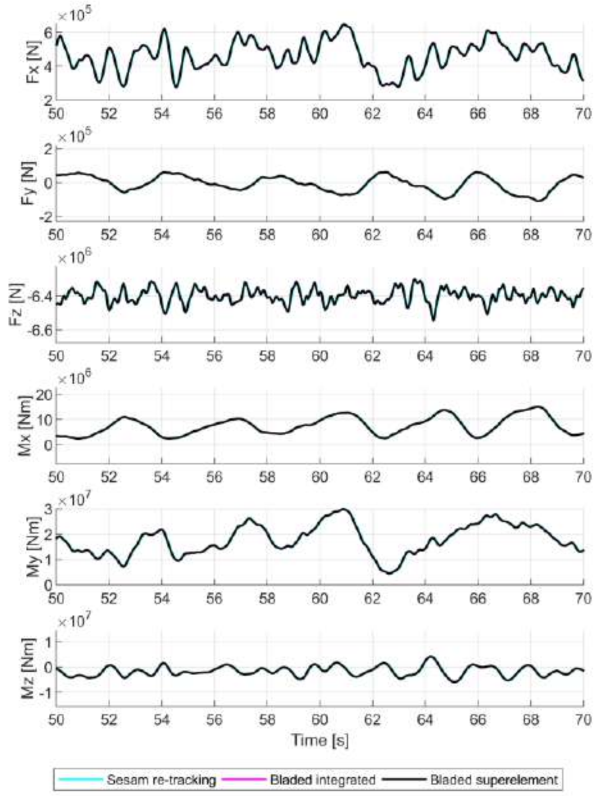

Figure A.1: Loads at the interface node.

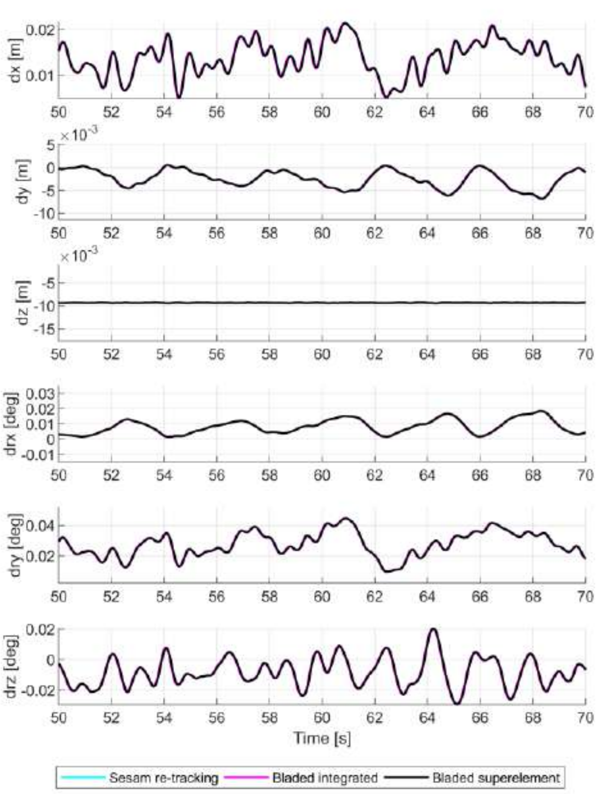

Figure A.2: Displacements at the interface node.

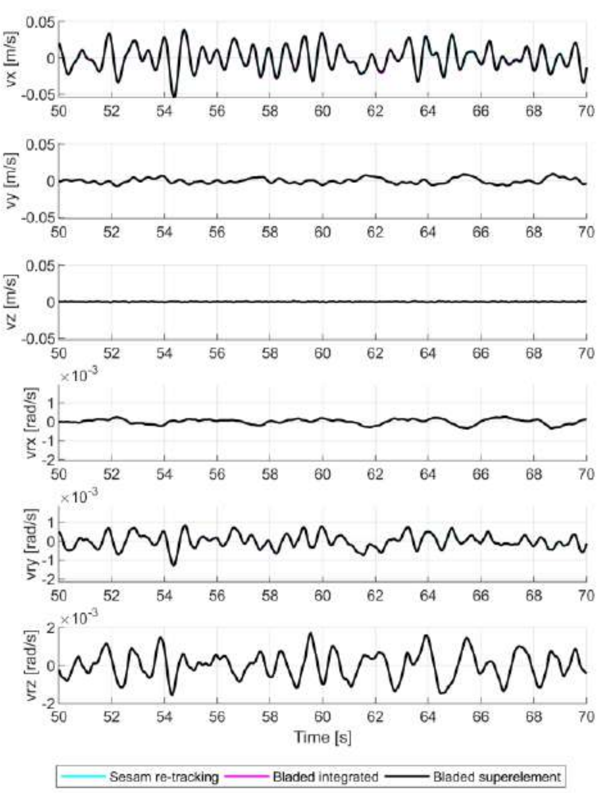

Figure A.3: Velocities at the interface node.

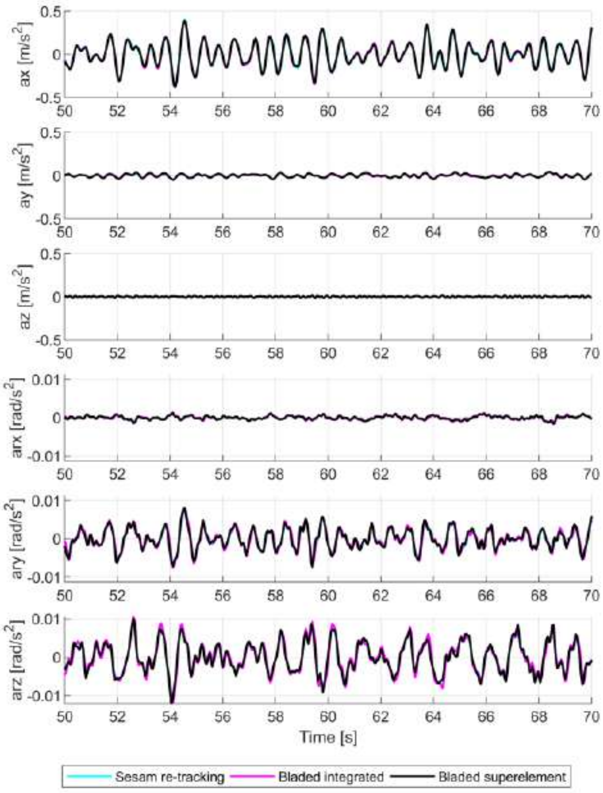

Figure A.4: Accelerations at the interface node.

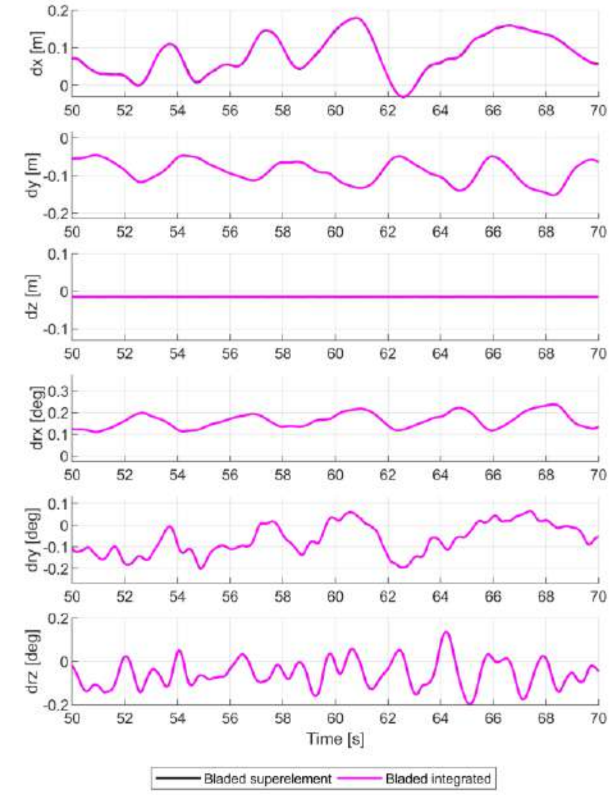

Figure A.5: Displacements and rotations at the tower top.

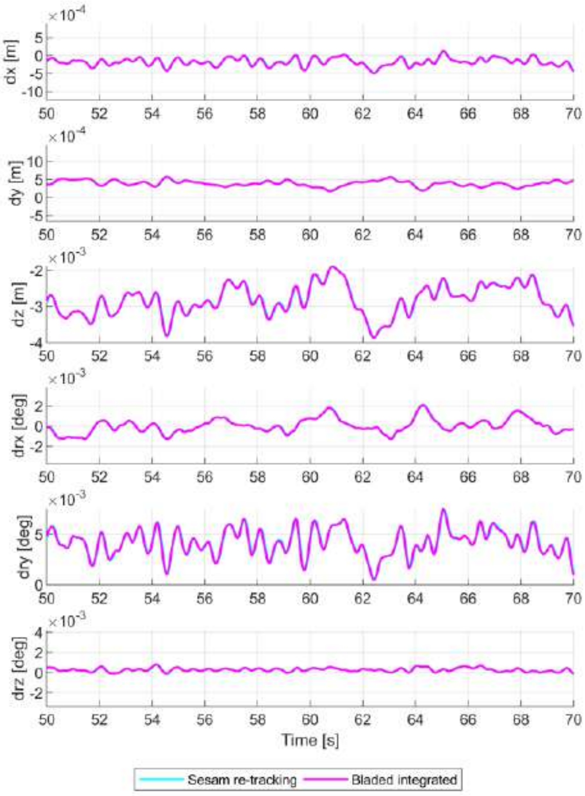

Figure A.6: Displacements and rotations at joint Jt_K_5_4.

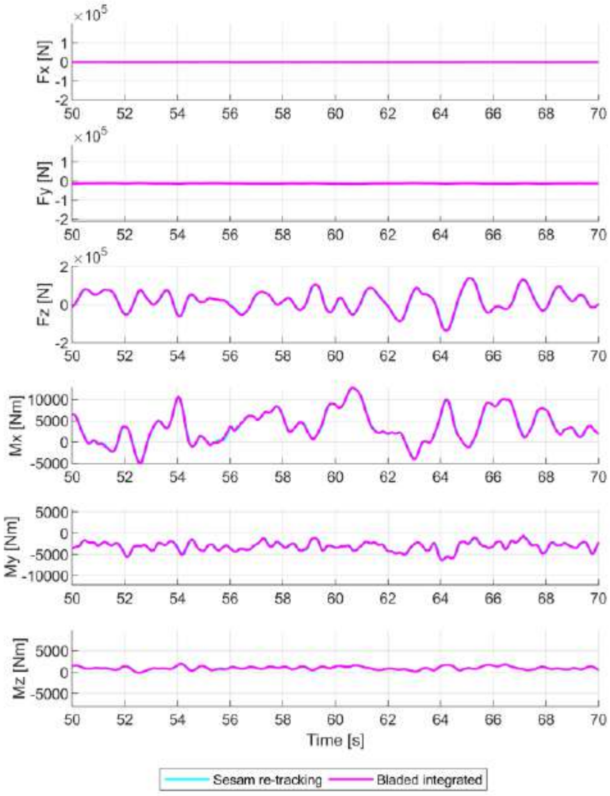

Figure A.7: X-brace forces and moments at Jt_X_1_3, element 27.

A.2 EXTREME LOAD CASE, REGULAR WAVE

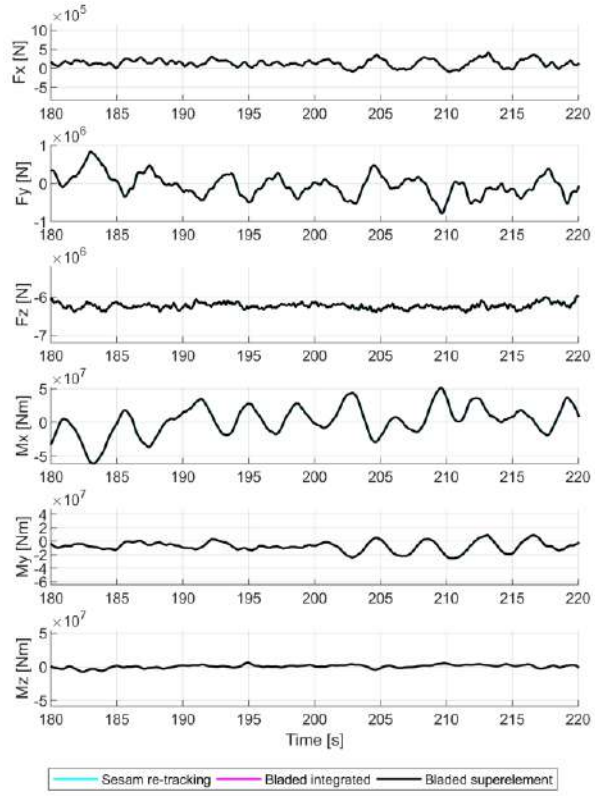

Figure A.8: Loads at the interface node.

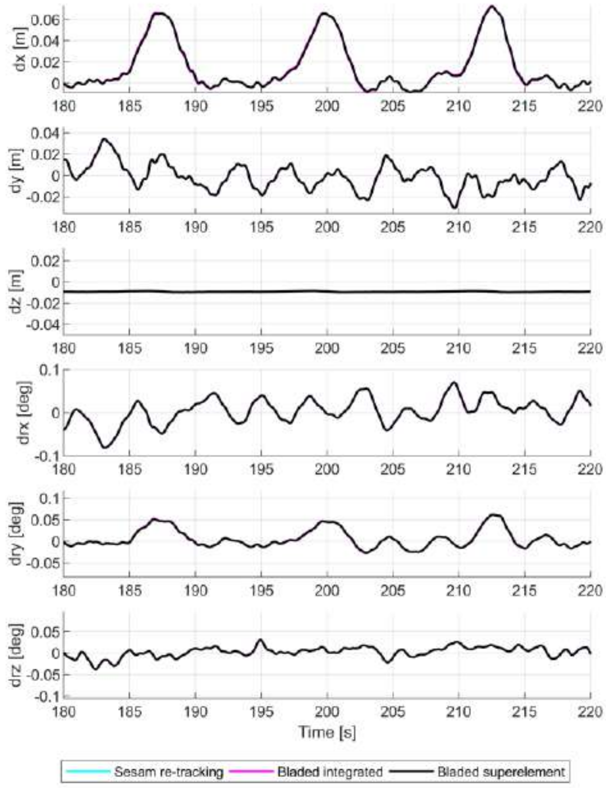

Figure A.9: Displacements at the interface node.

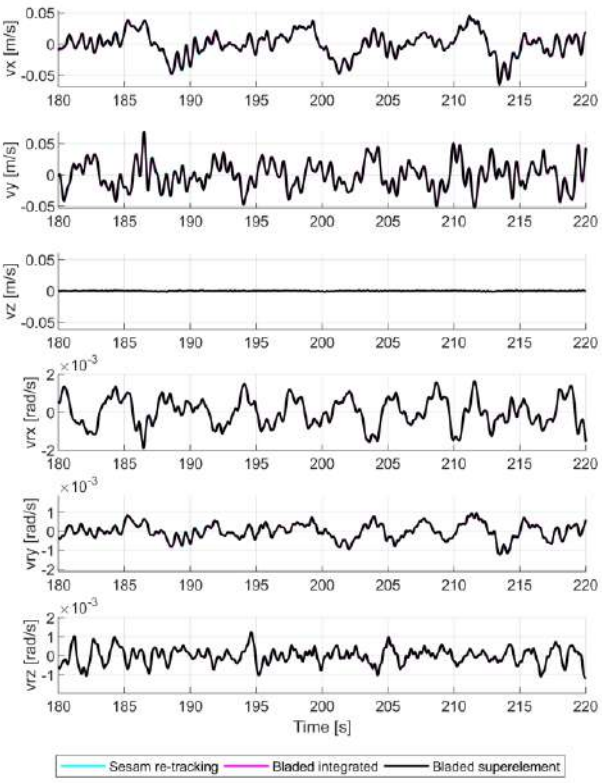

Figure A.10: Velocities at the interface node.

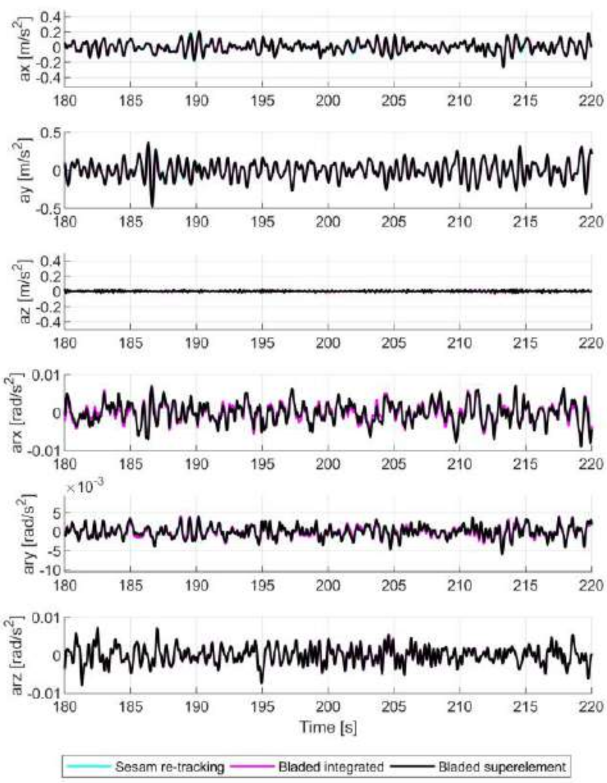

Figure A.11: Accelerations at the interface node.

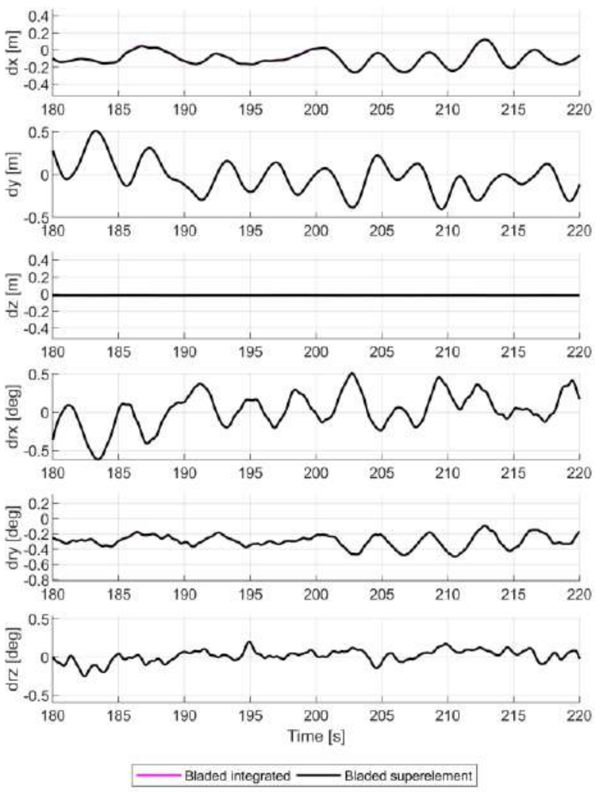

Figure A.12: Displacements and rotations at the tower top.

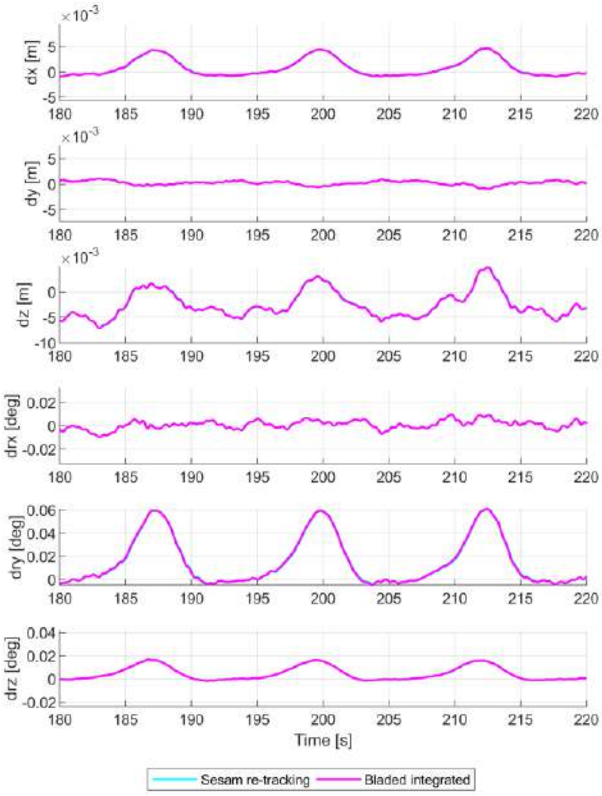

Figure A.13: Displacements and rotations at joint Jt_K_5_4.

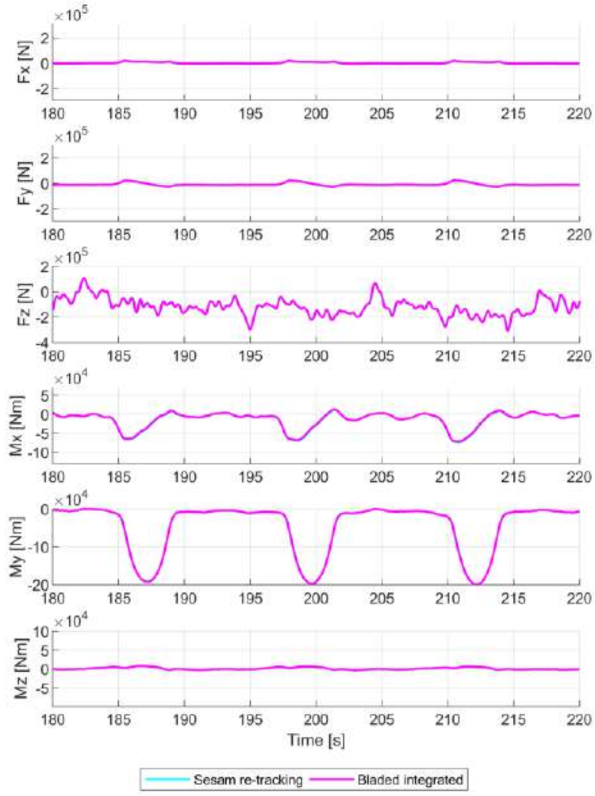

Figure A.14: X-brace forces and moments at Jt_X_1_3, element 27.