IMPLEMENTING AN INTERFACE BETWEEN BLADED AND SESAM

Verification report of Sesam's Bladed interface

DNV GL

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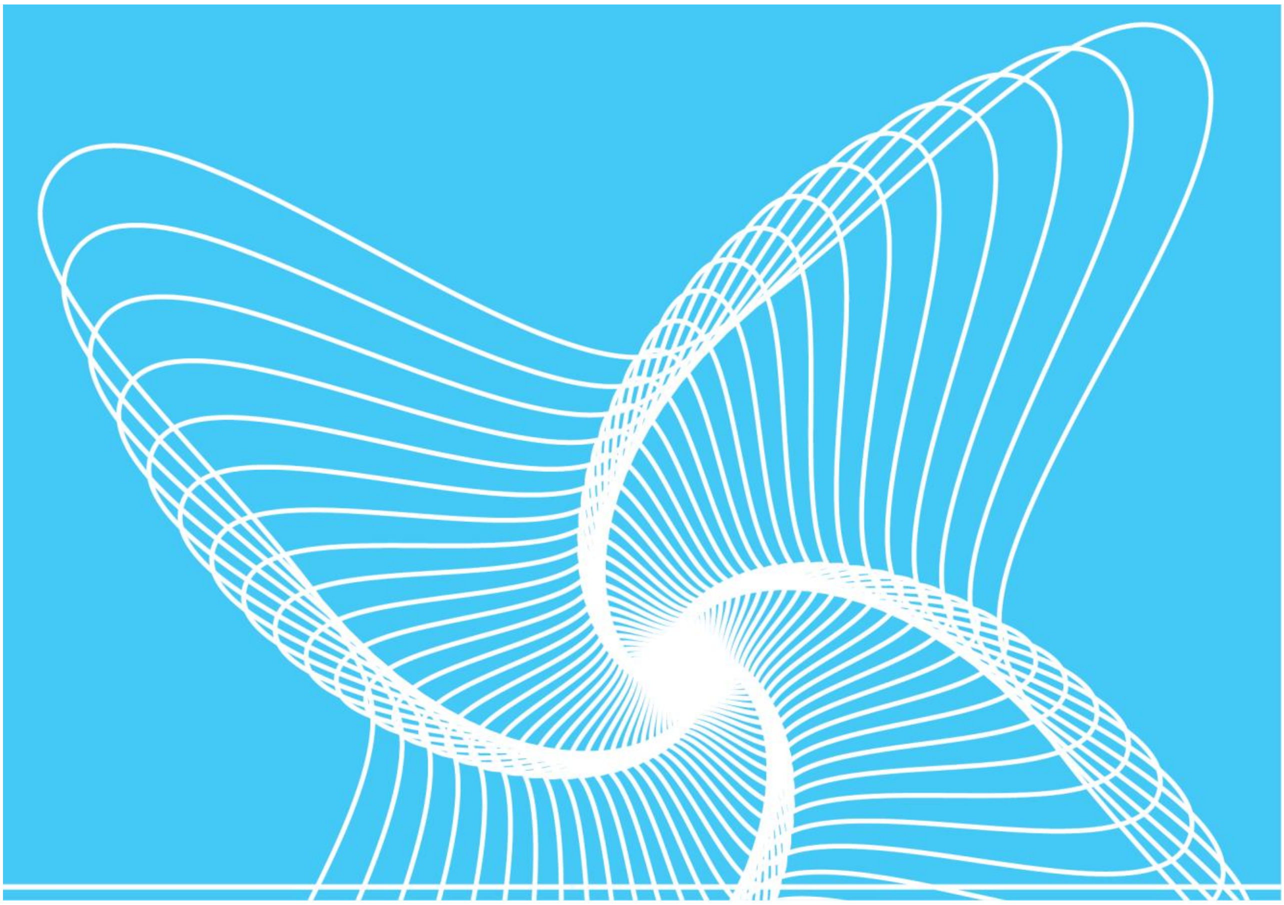

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Objective:

To document the implementation of the Bladed superelement analysis and integrated design interface in Sesam and to document the verification of this implementation.

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1 EXECUTIVE SUMMARY

In this document, the implementation of integrated design and superelement analysis workflows using DNV GL's Sesam and Bladed software packages is verified. In particular, the purpose of the study is to verify the conversion of the Sesam support structure model to both a Bladed integrated model and a Bladed superelement model and reduced wave load files, and check that the software packages give similar load and deflection predictions. The study also aims to verify the conversion of the results from Bladed into Sesam format, both for the full jacket load time series and for the superelement interface loads.

The verification study confirms that the conversions provided by Sesam to and from Bladed have been performed properly, both for the integrated model, for the superelement model and loads and for the results. It also shows that the superelement was properly converged. This means that the conversion from Sesam into Bladed and from Bladed into Sesam as implemented into Sesam's Fatigue Manager, as well as the spectral and spatial convergence runs, are functioning properly. It also shows that the superelement implementation in Bladed and interface load file export from Bladed is functioning properly.

This therefore allows a foundation designer to use Sesam together with Bladed in a single workflow, both for a superelement analysis as well as for an integrated design approach, with confidence in the accuracy of the conversions and results between the tools.

For the verification study, an offshore jacket has been designed that could support a generic 7 MW offshore wind turbine. Gravity and wave loads are applied to the structure and simulated for a 10-minute period for fatigue and extreme design load cases.

Bladed and Sesam can be used in a single workflow in two ways, either using an integrated design approach or using a superelement analysis. For the integrated approach, the jacket model is converted from Sesam format to Bladed format, including material and section data as well as hydrodynamic properties. For the superelement analysis, a superelement file and reduced wave load files are generated by Sesam and imported into Bladed. The superelement file consists of stiffness, damping and mass matrices as well as a reduced gravity vector. The wave load files contain the reduced wave load vector on the superelement. The superelement consists of six degrees of freedom at the interface combined with a number of additional internal modes, so that the superelement's response is close to that of the fully-modelled jacket, up to a certain frequency.

Sesam and Bladed make various different modelling and analysis assumptions for the structure and its environment. To allow the results of the two tools to be compared, some limitations were imposed during this verification study to match the modelling assumptions as closely as possible. Also for this reason, there are some limitations in the Sesam to Bladed converter. The most relevant differences are related to geometric stiffening, structural damping and wave load calculation. It should be noted that in a normal workflow one will use either the integrated or superelement workflow, thereby removing some of the limitations that were imposed on this comparison to match the modelling assumptions in order to compare both analysis types in both tools.

During the verification study it has been found that a jacket model can be properly converted from Sesam to Bladed for an integrated analysis. It was also found that all data required for a superelement analysis, i.e. mass, damping and stiffness matrix, gravity load vector and wave load vectors, can be obtained from Sesam and outputted into the required Bladed format correctly. The superelement data is obtained from a run with gravity and calm sea only (i.e. no wave loading) while the wave loading is obtained per design load case. The coordinate systems and wind and wave direction definitions are properly taken into account.

The jacket superelement that is used in the verification study has been checked for both spectral and spatial convergence. The spectral convergence runs show that the natural frequencies and mode shapes of the stand-alone jacket are similar for the full jacket in Sesam and for the superelement jacket, both in Sesam and Bladed. Also, the jacket model converted to Bladed for the integrated analysis matches closely to the original in Sesam. The same can be said when the jacket is combined with the wind turbine tower and point mass RNA, showing similar natural frequencies and mode shapes for both analysis types in both tools.

The wave surface elevation in Sesam (which is sent to Bladed in the reduced wave load files for the superelement runs) is the same as that used in Bladed in the integrated runs. It should be noted that this had to be reconstructed in Bladed for the integrated analysis, since the wave load time series generators in Sesam and Bladed use different methods to generate the waves based on random seeds. The wave components used in Sesam can be exported and used in Bladed in order to get an exact match of the wave components in both tools. In a normal project, one would however generate the wave in either Sesam or Bladed, thereby not having to go through the process of recreating the Sesam wave in Bladed.

Applying gravity and wave loads, the resulting loads and motions (displacement, velocity and acceleration) are compared at the interface, at some locations in the jacket and at the tower top. The results of the superelement runs in Bladed and Sesam match well and closely follow the results of the Sesam integrated model for all results. Some noticeable differences exist when comparing the results of the Bladed integrated model to the other three analyses for the case where the RNA is represented by a point mass. These differences are most likely caused by the differences in modelling, e.g. wave load calculation, damping, etc. in Sesam and Bladed. However, the results are comparable to those of the other three runs.

Tests were also carried out with an operating wind turbine on the support structure, including wind, wave and gravity loads. In this case, the results from the Sesam+Bladed superelement run compare well to the Bladed integrated run. This is the case for the fatigue and for the extreme load cases.

2 INTRODUCTION

In general, a dynamic time integration analysis using Sesam and Bladed can be performed in two ways:

Integrated analysis: The modelling of the jacket and tower is done in Sesam. The model is then imported/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. This is also known as a fully-coupled approach.

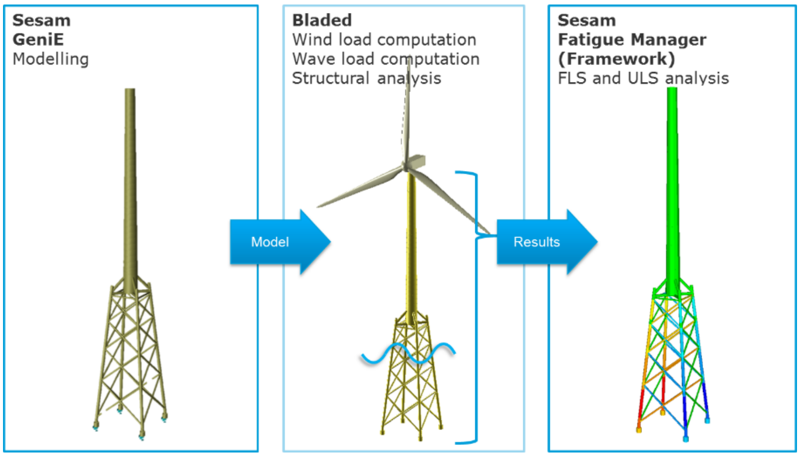


Figure 2-1 Integrated analysis workflow when using Sesam and Bladed

Superelement analysis: The modelling of the jacket is done in Sesam. The model and the wave loads are then reduced into a superelement and linked to a wind turbine and tower model in Bladed. A wind loads analysis 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 wave loads, and the structural analysis is run. Fatigue and extreme analysis is subsequently performed in Sesam. This is also known as a sequentially coupled approach.

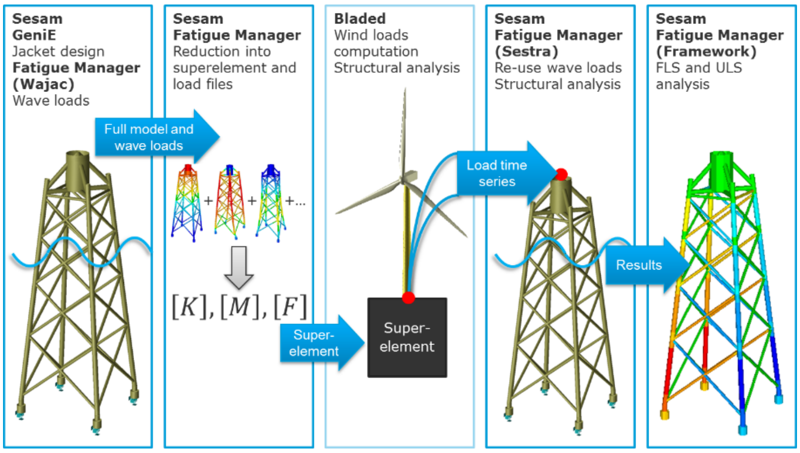


Figure 2-2 Superelement analysis workflow when using Sesam and Bladed

In this document both methods will be compared using both Sesam and Bladed. First, a comparison will be performed using a point mass instead of an actual wind turbine. This allows to compare an integrated model in Sesam to Bladed, as well as a superelement model in both tools. After this, the point mass is replaced by an actual wind turbine and a comparison of the integrated model in Bladed versus the superelement model using Sesam and Bladed is performed between the two methods.

For more information, to ask questions or to learn the best practice in using Sesam and Bladed for offshore wind turbine support structure analysis, please contact our support team via software.support@dnvgl.com. A workshop may be arranged upon request.

3 VERIFICATION SETUP

The approach used in the verification study as well as some model specifications and environmental settings are explained in this chapter.

3.1 Approach

The following approach is proposed to verify the implementation of the conversion from Sesam to Bladed and back. Two series of tests will be performed, with slightly different models, as explained in the following two sections.

3.1.1 Comparison using point mass RNA

Jacket including tower and rotor-nacelle assembly (RNA) modelled as a point mass. This structure will be analysed using an integrated approach and a superelement approach as follows:

1. Jacket structure with tower and RNA point mass in Sesam (Sesam integrated):
    a. Gravity and wave loads are generated in Sesam.
    b. A direct time integration analysis is performed in Sesam.
    c. Loads are extracted at the interface and other locations in the jacket.
2. Jacket structure converted as a superelement into Bladed. Tower and RNA are added in Bladed (Sesam-Bladed superelement). Gravity and wave loads on the jacket will be generated in Sesam, gravity will be applied to the tower and RNA point mass in Bladed.
    a. Gravity and wave loads (identical to those for the integrated structure in Sesam) are generated in Sesam.
    b. The model and loads are converted from Sesam to a Bladed superelement model and reduced wave loads file.
    c. The jacket superelement model is taken into Bladed and combined with the tower and point mass RNA.
    d. A load calculation is performed in Bladed using the reduced wave loads file.
    e. The interface loads are converted from Bladed to Sesam.
    f. The interface loads are applied to the jacket model in Sesam and a direct time integration analysis is performed.
    g. Results are extracted at the interface and other locations in the jacket.
3. Jacket structure and tower converted as a full model into Bladed. RNA point mass is added in Bladed (Bladed integrated). Gravity and wave loads will be generated in Bladed.
    a. The jacket and tower are converted from Sesam into Bladed.
    b. An RNA point mass is added to the structure.
    c. Gravity and wave loads (identical to those for the integrated structure in Sesam) are generated in Bladed.
    d. A direct time integration analysis is performed in Bladed.
    e. The complete results are converted from Bladed to Sesam.
    f. Results are extracted at the interface and other locations in the jacket.

For all three versions of the model, the mass, natural frequencies and mode shapes of the stand-alone jacket and jacket including tower and RNA point mass will be compared first. After that, gravity and wave loads are generated and a direct time integration analysis is performed. Loads, displacements, velocities and/or accelerations are extracted at the interface and other locations in the jacket and compared between the models.

3.1.2 Comparison using wind turbine RNA

Jacket including tower and wind turbine RNA. This structure will be analysed using an integrated approach and a superelement approach as follows (note that Sesam cannot model an actual wind turbine, so only the two Bladed methods remain):

1. Superelement approach (Sesam-Bladed superelement):
   a. Gravity and wave loads are generated in Sesam.
   b. The model and loads are converted from Sesam to a Bladed superelement model and reduced wave loads file.
   c. The jacket superelement model is taken into Bladed and combined with the tower and wind turbine RNA.
   d. A load calculation is performed in Bladed using the reduced wave loads file. Aerodynamic turbine loads are included in the analysis.
   e. The interface loads are converted from Bladed to Sesam.
   f. The interface loads are applied to the jacket model in Sesam and a direct time integration analysis is performed.
   g. Loads are extracted at the interface and other locations in the jacket.
2. Integrated approach (Bladed integrated):
   a. The complete structure is modelled in Bladed.
   b. A load calculation is performed in Bladed using gravity, wave loads (identical to those of the superelement approach) and aerodynamic loads (identical to those of the superelement approach) generated in Bladed.
   c. The complete results are converted from Bladed to Sesam.
   d. Loads are extracted at the interface and other locations in the jacket.

The results at the interface and other points in the jacket of the two different approaches are then compared.

3.2 Models used

The interface of the model is at a Z-coordinate of +27.4 m (above lowest astronomical tide (LAT)). The stand-alone jacket reaches up to this point and the superelement is generated up to this point.

The complete structure including jacket, tower and point mass RNA is shown in Figure 3-1 and Figure 3-2. The jacket in Sesam when converted to Bladed is shown in Figure 3-3 and Figure 3-4. The turbine assumed for the jacket is a 7MW generic turbine, with an RNA mass of 410 tonnes, rotor diameter of 154 m and hub height at 105 m.

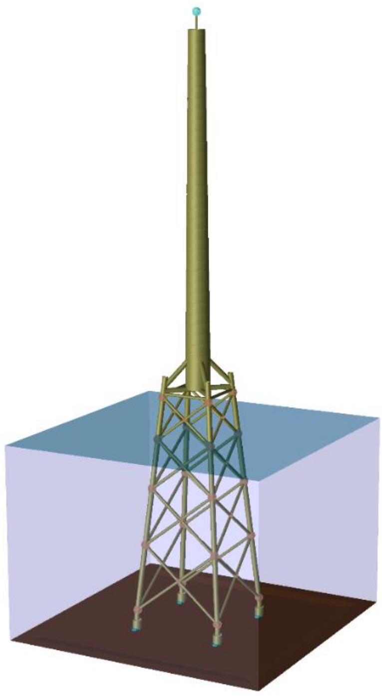


Figure 3-1 Jacket, tower and point mass RNA used in the verification study

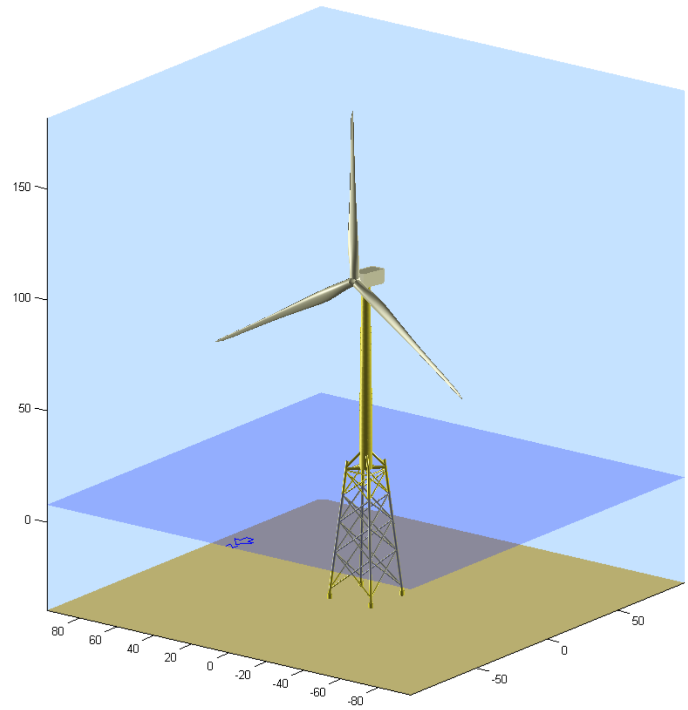


Figure 3-2 Jacket and wind turbine model used in the verification study

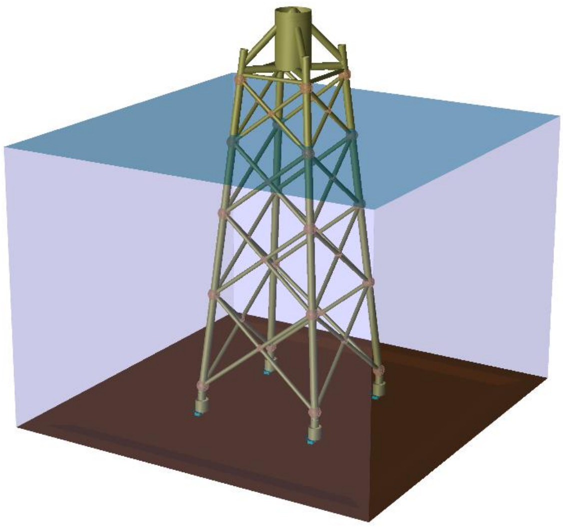


Figure 3-3 Jacket in Sesam

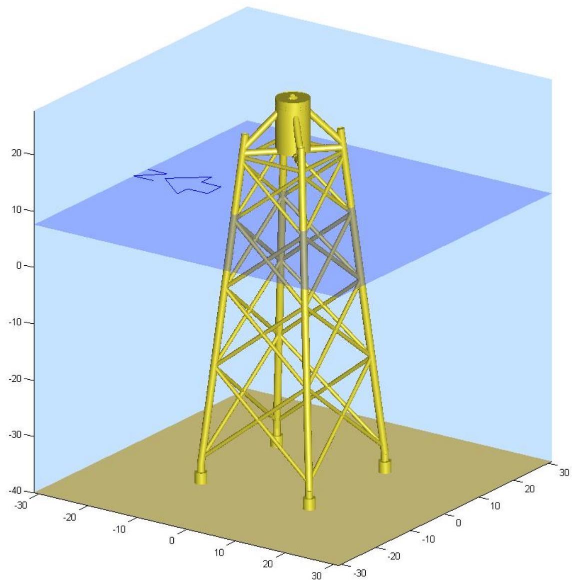


Figure 3-4 Jacket in Bladed

3.3 Location, wave and aerodynamic load setup

The turbine is modelled at a location with the properties as specified in Table 3-1.

Table 3-1 Site properties of the simulated jacket and turbine. Lowest astronomical tide (LAT) is defined with a Z-coordinate of 0.

Property	Value
Mean sea level	Z = 7.56 m
Mudline	Z = -40 m

Hydrodynamic properties have been assigned to the jacket. The legs have been flooded and Morison coefficients have been assigned to the jacket, but no marine growth has been assigned.

The default (fatigue) load case is described in Table 3-2. This is used for all simulations, unless noted otherwise.

Some simulations have been run using extreme conditions of wave and wind loading. These extreme load cases are described in Table 3-3.

Table 3-2 Default (fatigue) load case description. The wind related settings are only applicable for the simulations including a wind turbine.

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

Table 3-3 Extreme load case description. Multiple wave types are used in the different simulations in the comparison.

Parameter	Constrained case	Irregular case	Regular case
Wave type	Constrained (irregular + regular)	Irregular	Regular
Significant wave height, Hs	9.5 m	9.5 m	Wave height: 16 m
Zero-upcrossing period, Tz	9.45 s	9.45 s	Wave period: 12.5 s
Peak period, Tp	12.5 s	12.5 s	
Peak enhancement factor, gamma	3	3	N/A
Current	1.6 m/s over whole depth	1.6 m/s over whole depth	1.6 m/s over whole depth
Wave theory	Airy	Airy	Stream function 8th order
Constrained wave occurrence time	200 s	N/A	N/A
Constrained wave height	16 m	N/A	N/A
Constrained wave period	12.5 s	N/A	N/A
Constrained wave theory	NewWave + Stream function 8th order	N/A	N/A
Wind field	3D turbulent	3D turbulent	3D turbulent
Mean wind speed	50 m/s	50 m/s	50 m/s
Wind turbine state	Parked	Parked	Parked

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. Wave loads are linearly interpolated to the calculation time step (a larger wave load generation time step is used to save computation time, while not significantly influencing the wave loads).

3.4 Software versions used

The following Sesam and Bladed modules and versions have been used for the verification study:

- GeniE V7.3-15
- Wajac V6.9-05
- Sestra V8.8-02
- Fatigue Manager V3.5
- Bladed 4.8.0.40

For the added simulations in revision 2 of the report, the following Sesam and Bladed modules and versions have been used:

- Wajac V7.3-02
- Sestra V10.6-00
- Fatigue Manager V4.2-01
- Bladed 4.9

3.5 Coordinate systems

This document has been reported using the Sesam and Bladed global coordinate systems, which are identical. The integrated jacket + wind turbine (WTG) model has been modelled such that the RNA is pointing towards the negative global x-axis. The wave runs along the positive global x-axis (i.e. incoming towards the front of the turbine). The global z-axis is defined positive upwards. The global y-axis completes the right-hand system. This is visualized in Figure 3-5.

The wave and wind directions are specified using a different definition in Sesam versus Bladed, see Figure 3-5 and Figure 3-6 respectively. The directions in Sesam should be entered in the Sesam system. Since the wave and wind direction are used in the file names of the reduced wave load files for Bladed, the directions are converted into the Bladed definition by Fatigue Manager when creating the reduced wave load data files for Bladed. Transformation of wave and wind direction from Sesam to the Bladed reduced wave loads file name is as follows: $\alpha = 360° - \beta$, where α is the direction in Bladed and β is the direction in Sesam. Similarly, the transformation of wave and wind direction from the Bladed interface load file name to Sesam is: $\beta = 360° - \alpha$.

Since the superelement data and reduced wave load files are converted from Sesam into Bladed, and since both Sesam and Bladed use the same global coordinate system, the wave loads will be acting in the same direction in Bladed as in Sesam. However, the direction definition is something that one needs to take care of when entering the data into Sesam.

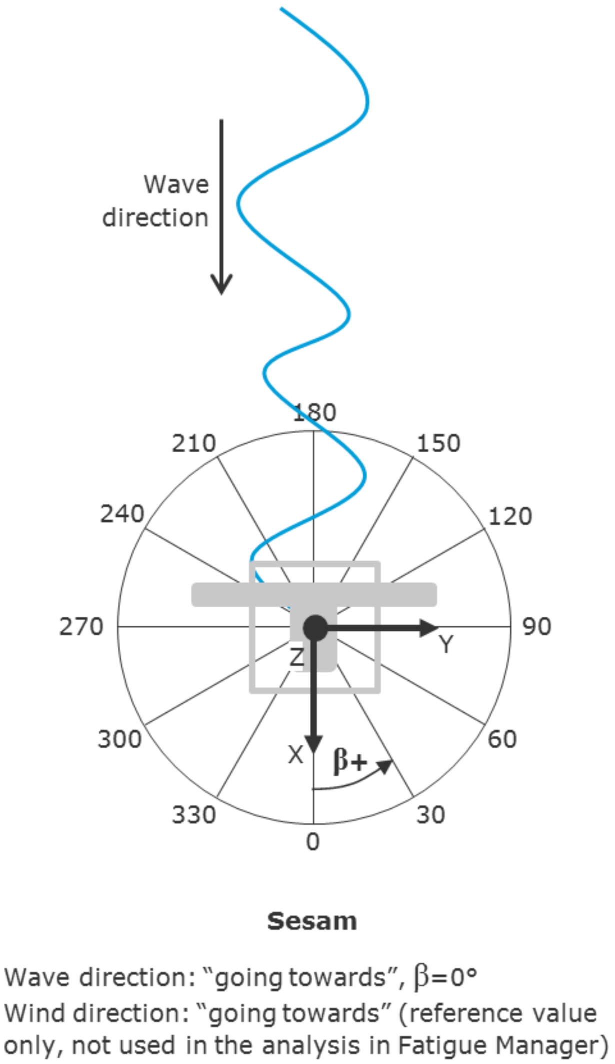


Figure 3-5 Global coordinate system and wave/wind direction definition in Sesam.

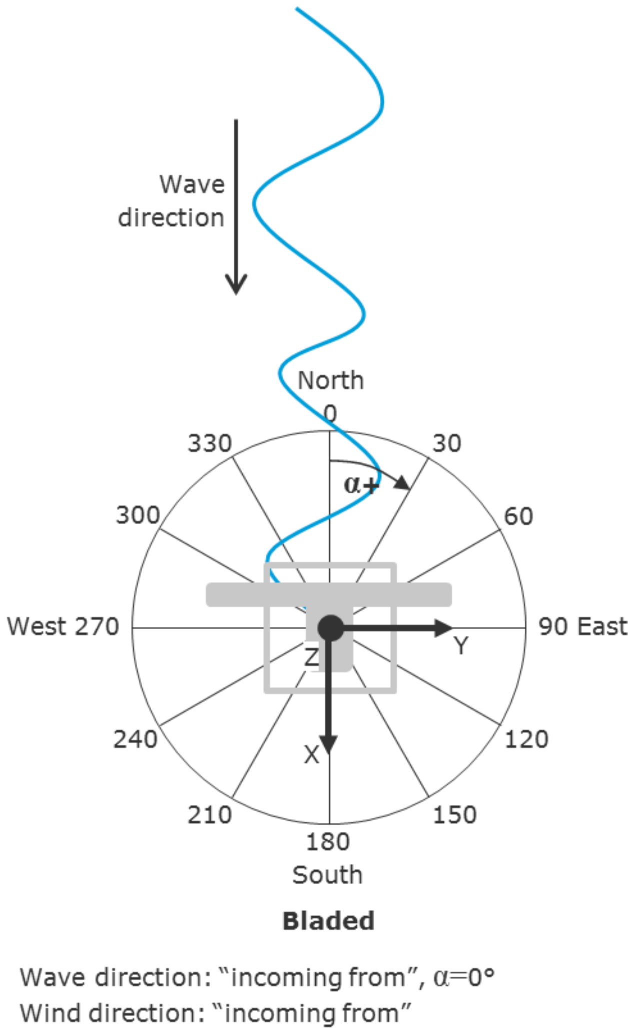


Figure 3-6 Global coordinate system and wave/wind direction definition in Bladed. Nacelle is displayed in accordance with the incoming wave. Default nacelle direction is towards North.

4 VERIFYING SUPERELEMENT CONVERSION

To perform a superelement wind turbine analysis in Bladed, the Sesam model needs to be exported to a superelement. The following chapter goes through the steps involved in creating a superelement for Bladed from Sesam.

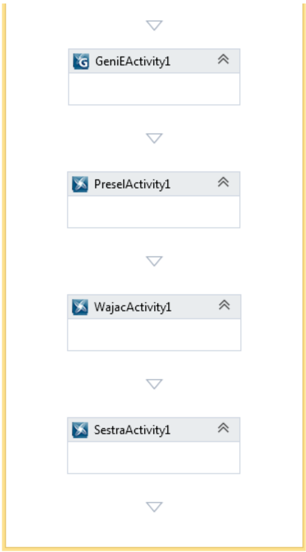
Note that the conversion process has been implemented into Sesam's Fatigue Manager, based on the process outlined in this chapter. Conversion is run automatically when converting a superelement model and loads to Bladed.

4.1 Process of generating superelement data

The process of converting a model into a superelement by Sesam's Fatigue Manager is based on the following steps.

4.1.1 M1.SIF with wave loads

Using a manual process in GeniE, a supernode is added to the jacket and using Presel a top-level superelement file is created. The process is as outlined below:



Sesam Manager

- Set up a Sesam Manager run with GeniE, Presel, Wajac and Sestra.

GeniE

- Import the structure.
- Include a 6 degrees of freedom supernode at the interface.
- Make sure no load cases are included.
- Mesh the model and save it as a T1.FEM file.

Presel

- Use the Presel input file from the workshop input files.
  Note: The number of load combinations created in Presel should equal the number of time steps that will be generated by Wajac.
- Import the FEM file from GeniE.
- Create a top level superelement.
- Create load combinations.
- Write out the top level superelement to T11.FEM.

Wajac

- Run Wajac including a time domain wave load computation, buoyancy and added mass.
- After Wajac has completed, the S1.FEM file in the _repository folder is opened and the third card on the LOHI command is changed from 12 (quasi-static) to 2 (dynamic analysis).
- The S1.FEM file is copied to S11.FEM in the _repository folder to be used by the top-level superelement.

Sestra

- In Sestra a forced response analysis based on modal superposition is executed, including the selected number of mode shapes.
- The MATR command is used to extract the mass and stiffness matrix and load vector at the interface. These will be written to M1.SIF.

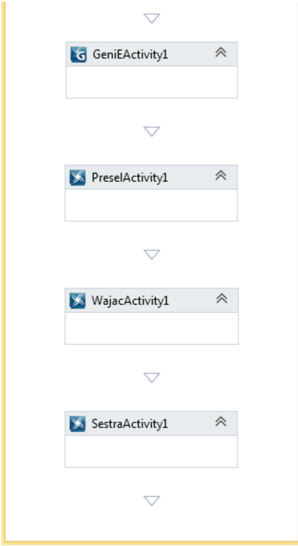
In the automated process in Fatigue Manager, the T1.FEM file without any supernodes is given as input. Fatigue Manager will add the supernode to the T1.FEM file. Similarly, the T11.FEM file is generated automatically by Fatigue Manager as well. Using the loads from Wajac, Sestra will be run to create

M1.SIF files which will be used to extract the mass and stiffness matrices and load vector for Bladed. Using the same input files, the same conversion is executed automatically in Fatigue Manager.

No significant differences in the stiffness matrix, mass matrix and load vector exist between the manual and automated approach, which means the data transferred to the M1.SIF file and superelement files after the Fatigue Manager run is correct.

4.1.2 Verifying M1.SIF with calm sea

The same verification is performed for files without a wave load, but with gravity and hydrodynamic added mass only (a calm sea state). To obtain a file with mass and stiffness matrix at the interface, as well as with the reduced gravity vector at the interface, the following steps need to be performed. The general process is the same, but with some differences (i.e. including gravity, not including a wave load and corresponding time steps):



Sesam Manager

- Set up a Sesam Manager run with GeniE, Presel, Wajac and Sestra.

GeniE

- Import the structure.
- Include a 6 degrees of freedom supernode at the interface.
- Include a gravity load case.
- Mesh the model and save it as a T1.FEM file.

Presel

The same Presel input file is used as before, but with a different amount of load combinations. The number of load combinations created in Presel should equal the number of load cases. Only one gravity case is included (the wave load time history is not generated for this run), so only one load combination is required in Presel.

- Import the FEM file from GeniE.
- Create a top level superelement.
- Create load combinations.
- Write out the top level superelement to T11.FEM.

Wajac

- The same Wajac input file is used, but the GRID, LOASIM, SEASIM and SPECTR commands are commented out/removed.

Sestra

- The same Sestra input file is used.
- Note that Wajac has not created an S#.FEM file for this run, so this has to be created manually. The S11.FEM file includes the following commands, using a single load case/time step only:

```
LOHI    1.   0.   2.   1.   1.   0.   0.   0.   0.    0.0000
TILO    1.    0.0000 2.000        0.0000     0.0000   0.0000
LCOM    1.    0.0000 2.000     1.000      1.000      1.0
```

- The S11.FEM file is placed in the _repository folder and the analysis is run.

For this run, only a single set of AMDLOAD cards is included on the M1.SIF file, representing the load case including gravity only. This will be the same for all time steps. The mass and stiffness matrix data is also the same for the runs with and without wave loads, which should be the case since both include hydrodynamic added mass.

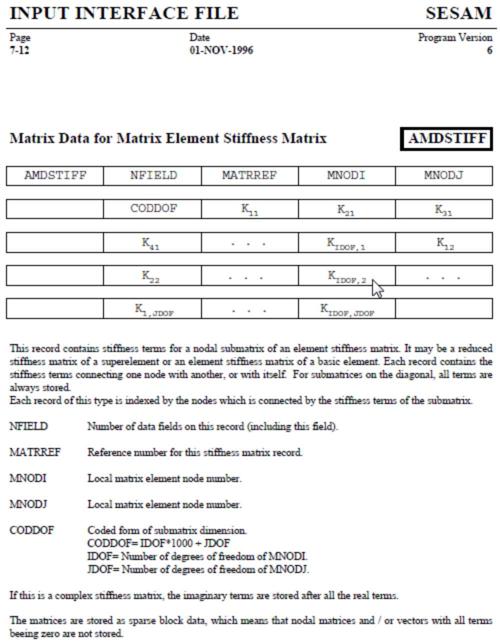
4.2 Verifying conversion to Bladed data format

With the data in the M1.SIF file properly created by Sestra via Fatigue Manager, the last step in the Bladed superelement conversion is writing out this data to the Bladed file format.

Data on the following cards in the M#.SIF file are of interest:

- AMDSTIF: stiffness matrix data
- AMDMASS: mass matrix data
- AMDLOAD: load vector data

NOTE: See the Sesam Input Interface File description [1] for a detailed specification of each card.



INPUT INTERFACE FILE **SESAM**

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Matrix Data for Matrix Element Stiffness Matrix **AMDSTIFF**

AMDSTIFF	NFIELD	MATRREF	MNODI	MNODJ
	CODDOF	K_{11}	K_{21}	K_{31}
	K_{41}	. . .	$K_{IDOF,1}$	K_{12}
	K_{22}	. . .	$K_{IDOF,2}$	. . .
	$K_{1,JDOF}$	. . .	$K_{IDOF,JDOF}$	

This record contains stiffness terms for a nodal submatrix of an element stiffness matrix. It may be a reduced stiffness matrix of a superelement or an element stiffness matrix of a basic element. Each record contains the stiffness terms connecting one node with another, or with itself. For submatrices on the diagonal, all terms are always stored.
Each record of this type is indexed by the nodes which is connected by the stiffness terms of the submatrix.

NFIELD Number of data fields on this record (including this field).

MATRREF Reference number for this stiffness matrix record.

MNODI Local matrix element node number.

MNODJ Local matrix element node number.

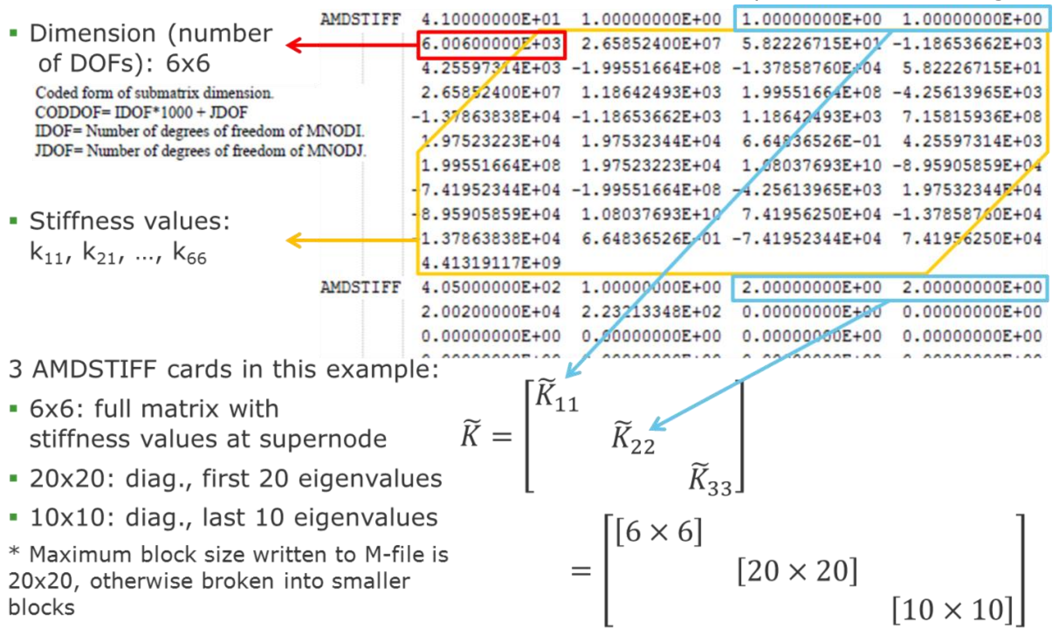
CODDOF Coded form of submatrix dimension.
CODDOF= IDOF*1000 + JDOF
IDOF= Number of degrees of freedom of MNODI.
JDOF= Number of degrees of freedom of MNODJ.

If this is a complex stiffness matrix, the imaginary terms are stored after all the real terms.

The matrices are stored as sparse block data, which means that nodal matrices and / or vectors with all terms beeing zero are not stored.

4.2.1 Stiffness matrix

The stiffness matrix is written on the AMDSTIFF cards, for a superelement including 30 mode shapes.

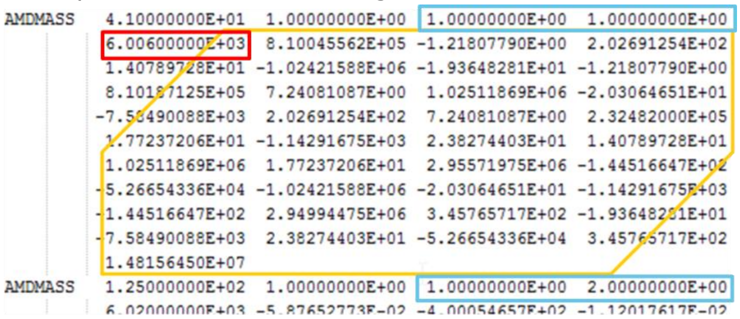


The stiffness matrix is the same for all runs within a conversion, since all are using the same model, gravity and mean sea level. This will result in a constant superelement for all runs within a conversion. The stiffness matrix of the superelement is taken from a separate conversion run with gravity and calm sea only (i.e. no wave loads).

4.2.2 Mass matrix

Similarly, the mass matrix is written on the AMDMASS cards, for a superelement including 30 mode shapes. Note that the matrix is symmetric around the diagonal.

- Similar to AMDSTIFF, but contains mass values
- More off-diagonal terms
- Symmetric around diagonal
- 5 AMDMASS in this example


```
AMDMASS   4.10000000E+01  1.00000000E+00  1.00000000E+00  1.00000000E+00
          6.00600000E+03  8.10045562E+05 -1.21807790E+00  2.02691254E+02
          1.40789728E+01 -1.02421588E+06 -1.93648281E+01 -1.21807790E+00
          8.10187125E+05  7.24081087E+00  1.02511869E+06 -2.03064651E+01
         -7.58490088E+03  2.02691254E+02  7.24081087E+00  2.32482000E+05
          1.77237206E+01 -1.14291675E+03  2.38274403E+01  1.40789728E+01
          1.02511869E+06  1.77237206E+01  2.95571975E+06 -1.44516647E+02
         -5.26654336E+04 -1.02421588E+06 -2.03064651E+01 -1.14291675E+03
         -1.44516647E+02  2.94994475E+06  3.45765717E+02 -1.93648281E+01
         -7.58490088E+03  2.38274403E+01 -5.26654336E+04  3.45765717E+02
          1.48156450E+07
AMDMASS   1.25000000E+02  1.00000000E+00  1.00000000E+00  2.00000000E+00
```

$$\widetilde{M} = \begin{bmatrix} \widetilde{M}_{11} & \widetilde{M}_{12} & \widetilde{M}_{13} \\ & \widetilde{M}_{22} & \\ & & \widetilde{M}_{33} \end{bmatrix}$$

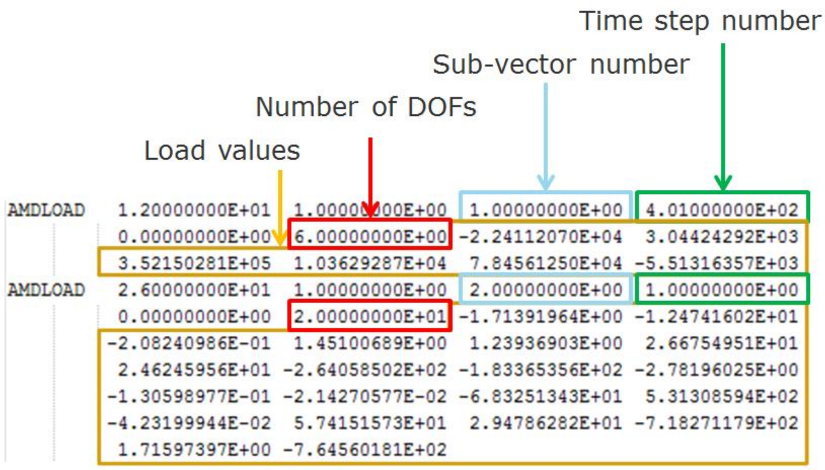
$$= \begin{bmatrix} [6\times 6] & [6\times 20] & [6\times 10] \\ & [20\times 20] & \\ & & [10\times 10] \end{bmatrix}$$

As for the stiffness matrix, the mass matrix is the same for all runs within a conversion, since all are using the same model, gravity and mean sea level. This will result in a constant superelement for all runs within a conversion. The mass matrix of the superelement is taken from a separate conversion run with gravity and calm sea only (i.e. no wave loads), so it also includes hydrodynamic added mass.

4.2.3 Load vector

The load vector is written to the AMDLOAD cards. Per card, it contains the load values at each node, for each time step.

- Contains load values at each node, for each time step



```
AMDLOAD   1.20000000E+01  1.00000000E+00  1.00000000E+00  4.01000000E+02
          0.00000000E+00  6.00000000E+00 -2.24112070E+04  3.04424292E+03
          3.52150281E+05  1.03629287E+04  7.84561250E+04 -5.51316357E+03
AMDLOAD   2.60000000E+01  1.00000000E+00  2.00000000E+00  1.00000000E+00
          0.00000000E+00  2.00000000E+01 -1.71391964E+00 -1.24741602E+01
         -2.08240986E-01  1.45100689E+00  1.23936903E+00  2.66754951E+01
          2.46245956E+01 -2.64058502E+02 -1.83365356E+02 -2.78196025E+00
         -1.30598977E-01 -2.14270577E-02 -6.83251343E+01  5.31308594E+02
         -4.23199944E-02  5.74151573E+01  2.94786282E+01 -7.18271179E+02
          1.71597397E+00 -7.64560181E+02
```

$$\tilde{f} = [\tilde{f}_1 \quad \tilde{f}_2 \quad \tilde{f}_3]$$

$$= [time\ steps \times 6 \quad time\ steps \times 20 \quad time\ steps \times 10]$$

$$= [time\ steps \times 36]$$

All loads applied to the model are combined in the AMDLOAD cards. Therefore, a separate run is required to identify the gravity load vector independently from the wave load vector. This corresponds to the two different runs and M1.SIF files described in section 4.1.1 and 4.1.2. Since the gravity load vector is constant, only one run needs to be run to obtain this. Each design load case will have its own run to obtain the corresponding wave load vector.

Two types of load vectors are resulting from the conversion run:

- The first type of load vector is the reduced gravity load vector. This is constant for the superelement and is resulting from a single run with gravity and calm sea only. As for the stiffness and mass matrix, the gravity load vector is the same for all runs within a conversion, since all are using the same model, gravity and mean sea level. The gravity load vector is written to the superelement file together with the mass and stiffness matrix. This will result in a constant superelement for all runs within a conversion.
- The second type of load vector is that resulting from the wave load run of each design load case. One reduced wave load vector will result for each wave load run, including all hydrodynamic loads on the superelement. Note that no gravity is included in these runs, since otherwise gravity would be included into the AMDLOAD cards in the resulting M1.SIF files for these runs too, which would mean that gravity would have been included into Bladed twice (once through the gravity load vector and also through the wave load vector). The only purpose of these runs is to compute the wave loads on the jacket and to obtain the reduced wave load vector on the superelement.

4.2.4 Superelement and wave load files for Bladed

The mass matrix, stiffness matrix and gravity vector are written to the superelement file, named superelement.dat following the format as specified in reference [2]. In Figure 4-1 an example superelement.dat file is shown. Note that the damping matrix written to the file is empty (i.e. containing zero entries only). This allows the wind turbine manufacturer to decide the damping and inform the foundation designer of the desired damping values. Alternatively, the foundation designer can decide the damping matrix, e.g. based on Rayleigh coefficients. From Fatigue Manager V4.2, the damping matrix can be generated automatically based on the mass and stiffness matrices and user-specified Rayleigh coefficients.

```
1
1    1.10000000E+01    Jacket7MW_sup_
1      Mass
      4.97119969E+05  -8.16589374E-09   1.87190921E-08  -8.20408275E-09  -1.97519138E+06   1.22845137E-07  -1.82053406E-09   3.45230621E+02   1.68511009E+01  -6.25544061E-12   8.87567575E-10
     -8.16589374E-09   4.97119969E+05  -1.85232842E-08   1.97519138E+06   1.06661915E-08   1.50953070E-07   1.47313428E-09   1.68511009E+01  -3.45230621E+02  -7.43805018E-10   8.86329288E-10
      1.87190921E-08  -1.85232842E-08   5.73927000E+05  -1.32009816E-07  -9.64573204E-08  -2.45912202E-09  -5.78545805E-12   1.54794233E-11   4.65209815E-10  -2.71076651E-12  -1.20874834E+01
     -8.20408275E-09   1.97519138E+06  -1.32009816E-07   1.00933940E+07  -1.42816958E-07   6.72804958E-07   9.59903179E-09   1.09634476E+02  -2.24609521E+03  -4.60729233E-09   5.35092859E-09
     -1.97519138E+06   1.06661915E-08  -9.64573204E-08  -1.42816958E-07   1.00933940E+07  -5.55257884E-07   1.18794929E-08  -2.24609521E+03  -1.09634476E+02  -1.41044509E-10  -4.73090411E-09
      1.22845137E-07   1.50953070E-07  -2.45912202E-09   6.72804958E-07  -5.55257884E-07   2.78102125E+06  -1.54549186E-11   2.67005529E-10   1.84819982E-09  -1.30311218E+03  -1.58814867E-12
     -1.82053406E-09   1.47313428E-09  -5.78545805E-12   9.59903179E-09   1.18794929E-08  -1.54549186E-11   1.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      3.45230621E+02   1.68511009E+01   1.54794233E-11   1.09634476E+02  -2.24609521E+03   2.67005529E-10   0.00000000E+00   1.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      1.68511009E+01  -3.45230621E+02   4.65209815E-10  -2.24609521E+03  -1.09634476E+02   1.84819982E-09   0.00000000E+00   0.00000000E+00   1.00000000E+00   0.00000000E+00   0.00000000E+00
     -6.25544061E-12  -7.43805018E-10  -2.71076651E-12  -4.60729233E-09  -1.41044509E-10  -1.30311218E+03   0.00000000E+00   0.00000000E+00   0.00000000E+00   1.00000000E+00   0.00000000E+00
      8.87567575E-10   8.86329288E-10  -1.20874834E+01   5.35092859E-09  -4.73090411E-09  -1.58814867E-12   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   1.00000000E+00
2     Damping
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
3     Stiffness
      8.24195040E+07   4.02392470E-06  -6.65094740E-06   1.27442181E-05  -1.37239130E+09  -1.59751857E-04   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      4.02392470E-06   8.24195040E+07   3.34936976E-06   1.37239130E+09  -4.18042764E-05  -1.72684668E-04   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
     -6.65094740E-06   3.34936976E-06   1.34204570E+09   2.85135000E-04   1.64690326E-04   1.50727183E-05   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      1.27442181E-05   1.37239130E+09   2.85135000E-04   7.56143063E+10   2.91481614E-04  -6.36644661E-04   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
     -1.37239130E+09  -4.18042764E-05   1.64690326E-04   2.91481614E-04   7.56143063E+10   6.09137118E-04   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
     -1.59751857E-04  -1.72684668E-04   1.50727183E-05  -6.36644661E-04   6.09137118E-04   1.16128164E+10   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   9.69128845E+02   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   9.74236816E+02   0.00000000E+00   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   9.74236816E+02   0.00000000E+00   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   1.22378247E+03   0.00000000E+00
      0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   0.00000000E+00   1.50748389E+03
4  Gravity load vector [N]/[Nm]
     -5.74727892E-08
     -8.49831849E-09
     -7.58055200E+06
      2.62982212E-07
      2.85916030E-07
      1.85973477E-08
      1.00208054E-11
     -7.91278154E-12
     -6.92553570E-09
      1.66796542E-11
     -2.20176712E+02
```

Figure 4-1 Example superelement.dat file created by Fatigue Manager, for display purposes only including 5 modes

The wave load files contain the time step and reduced wave load for each time step as well as the surface elevation. The data is written to a .dat file as well, but the file name depends on the design load case specifications as entered into Fatigue Manager. An example wave load data file is shown in Figure 4-2.

```
8
0        1.10000000E+01 Jacket7MW_sup_
0.0
2001
0.00    -4.38057930E+01  1.11089190E-05  1.44352162E+03  9.08686891E-05  2.46491078E+02  2.24363003E-05 -1.87510738E-02 -6.78745575E-02 -3.70399356E-03 -2.56450385E-08  6.45736618E-02 -1.337
0.10    -3.76550938E+01 -3.58994235E-06  1.44453238E+03 -2.26733424E-05  2.10534953E+02  6.75581954E-06 -1.98180294E-02 -5.76298409E-02 -3.14489770E-03 -5.86129499E-09  6.44663696E-02 -1.348
0.20    -3.11923906E+01 -6.32444909E-06  1.44594588E+03 -5.29170409E-05  1.73119859E+02  9.07550380E-06 -2.08080788E-02 -4.69918098E-02 -2.56435943E-03 -7.98168185E-09  6.43890839E-02 -1.332
0.30    -2.44472539E+01 -2.19579367E-06  1.44776725E+03 -2.12135557E-05  1.34350188E+02 -1.52676860E-05 -2.16946716E-02 -3.59766006E-02 -1.96326220E-03  1.68805800E-08  6.43374634E-02 -1.313
0.40    -1.71095215E+01 -5.82826510E-06  1.45008525E+03 -4.74231094E-05  9.33562266E+01  2.61283852E-05 -2.24865398E-02 -2.44891109E-02 -1.33637476E-03 -2.49726763E-08  6.42955704E-02 -1.285
0.50    -9.34738477E+00  4.74458188E-06  1.45303612E+03  4.00736108E-05  5.15560781E+01 -9.75779723E-06 -2.31755810E-02 -1.28833027E-02 -7.03064919E-04  1.23524233E-08  6.42571716E-02 -1.259
0.60    -1.37578882E+00  1.74622983E-13  1.45653000E+03 -7.01402314E-11  9.73276953E+00 -2.05909600E-12 -2.37373352E-02 -1.20836055E-03 -6.59411326E-05 -6.01854677E-15  6.42152252E-02 -1.24
0.70     5.87993457E+00  1.40129821E-06  1.46082100E+03  1.02213789E-05 -2.75084668E+01 -1.53304888E-05 -2.41311874E-02  9.61578846E-03  5.24737895E-04  1.69237919E-08  6.42521896E-02 -1.232
0.80     1.34804590E+01 -2.78077391E-06  1.46360600E+03 -2.11292636E-05 -6.82513594E+01 -1.66062880E-05 -2.43386250E-02  2.09632759E-02  1.14398956E-03  1.82774620E-08  6.43172226E-02 -1.235
0.90     2.08659004E+01 -4.61356575E-06  1.46660150E+03 -3.24564911E-05 -1.08853227E+02 -4.34731832E-06 -2.43404331E-02  3.21839981E-02  1.75631332E-03  6.10952611E-09  6.44165421E-02 -1.258
1.00     2.78194512E+01  2.61400896E-06  1.46949662E+03  1.12012550E-05 -1.48030234E+02  1.21842977E-05 -2.41203232E-02  4.30355492E-02  2.34847927E-03 -1.29525970E-08  6.45424347E-02 -1.279
1.10     3.41621797E+01  7.79039133E-06  1.47212562E+03  5.41446432E-05 -1.84373109E+02 -6.72493596E-06 -2.36754665E-02  5.32185974E-02  2.90416217E-03  5.84003192E-09  6.46915512E-02 -1.3
1.20     4.03439688E+01  4.33204323E-06  1.47548988E+03  3.40047702E-05 -2.20892297E+02  9.21590533E-06 -2.29960041E-02  6.32802048E-02  3.45323682E-03 -1.01479354E-08  6.49192429E-02 -1.309
1.30     4.58685195E+01  5.24787698E-06  1.47751862E+03  4.36503850E-05 -2.52433953E+02 -1.58752017E-05 -2.20841198E-02  7.22086945E-02  3.94046831E-03  1.75365240E-08  6.51763687E-02 -1.276
```

Figure 4-2 Example reduced wave load data file created by Fatigue Manager, for display purposes only including 5 modes

Care should be taken with the units of the required output. By default, SI units are used for all output from Sesam (assuming the user does not change the units during input). However, for the reduced wave load data file, the required unit is kN (see [2]), while the superelement file is in N.

5 VERIFYING SUPERELEMENT CONVERGENCE

Before a result comparison can be performed, a valid superelement needs to be created. The output from Fatigue Manager has been confirmed to be in accordance with the specifications (see [2]), but the superelement data itself needs to be converged too. The verification requirements relate to spectral convergence and spatial convergence. The following chapter goes through the steps involved in verifying a superelement from Sesam manually.

Note that the verification process has been implemented into Fatigue Manager, allowing spatial and spectral convergence to be run easily in Fatigue Manager.

5.1 Verifying spectral convergence

The standalone jacket mode shapes of the superelement model are compared to the full standalone jacket model in this section. Note that the mode shapes of jacket with tower and RNA point mass are compared in chapter 6 using the results from Bladed after adding the superelement model to the simplified WTG model in Bladed.

GeniE is used to obtain the eigenfrequencies of the jacket. The tower and RNA are excluded. The Wajac activity is set to only compute added mass and to take into account internal water. The free interface natural frequencies of the standalone jacket up to a frequency of 10 Hz are listed in Table 5-1.

Obtaining the eigenfrequencies and mode shapes for the superelement model requires reducing the full structure to a superelement without using any time domain loads. However, calm sea is included via Wajac to account for the hydrodynamic added mass effect on the natural frequencies of the jacket. This process has been implemented as an automated run into Fatigue Manager.

The number of mode shapes can be adjusted iteratively until spectral convergence is reached. For the model at hand, a comparison was made between the eigenfrequencies of the full and reduced (superelement) model for the number of modes included. The maximum error of the first 20 modes (up to and including the first modes above 10 Hz) was compared. Including 40 modes or more into the superelement will ensure that the maximum error in natural frequency between the full and reduced model is maximum 0.5% for these 20 modes.

The natural frequencies from Sestra and the mode shapes in Xtract are compared, to check whether modes have switched number and to compare the mode shapes between the full and reduced model. The modes up to the required 10 Hz are very similar in the full model and superelement model, with relative differences of maximum 0.5%. The free interface natural frequencies of the standalone jacket up to a frequency of 10 Hz for the superelement model including 40 modes (46 DOFs) is shown in Table 5-1.

Table 5-1 The free interface natural frequencies of the standalone jacket for the full model and superelement model including 40 modes (46 DOFs) in Sesam, up to a frequency of 10 Hz.

	Full model		Reduced model		Absolute error	Relative error
Mode	Freq. [Hz]	Period [s]	Freq. [Hz]	Period [s]	Freq. [Hz]	Freq. [%]
1	1.783	0.561	1.784	0.560	-0.001	-0.06 %
2	1.783	0.561	1.784	0.560	-0.001	-0.06 %
3	4.955	0.202	4.955	0.202	0.000	0.00 %
4	5.084	0.197	5.085	0.197	-0.001	-0.02 %
5	5.365	0.186	5.369	0.186	-0.004	-0.07 %
6	5.365	0.186	5.369	0.186	-0.004	-0.07 %
7	6.177	0.162	6.177	0.162	0.000	0.00 %
8	6.425	0.156	6.425	0.156	0.000	0.00 %
9	6.592	0.152	6.592	0.152	0.000	0.00 %
10	6.945	0.144	6.980	0.143	-0.035	-0.50 %

11	6.964	0.144	6.988	0.143	-0.024	-0.34 %
12	6.964	0.144	6.988	0.143	-0.024	-0.34 %
13	8.156	0.123	8.179	0.122	-0.023	-0.28 %
14	8.156	0.123	8.179	0.122	-0.023	-0.28 %
15	8.232	0.121	8.232	0.121	0.000	0.00 %
16	9.096	0.110	9.096	0.110	0.000	0.00 %
17	10.298	0.097	10.317	0.097	-0.019	-0.18 %
18	10.298	0.097	10.317	0.097	-0.019	-0.18 %
19	10.583	0.094	10.605	0.094	-0.022	-0.21 %
20	10.936	0.091	10.936	0.091	0.000	0.00 %

Note that in some of the higher modes some differences can be observed. This can be solved by including more modes into the superelement. However, since these modes are above 10 Hz, no further modes are included here. Note that including more modes would also improve the accuracy for the lower modes, since the eigenvalue analysis on the reduced structure would have more degrees of freedom.

5.1.1 Additional verification of superelement data

An additional check to verify that the superelement data is correct can be done by calculating the eigenvalues of the reduced mass and stiffness matrices, e.g. using a program such as Matlab.

To verify the reduced stiffness matrix, the following line of Matlab code can be used, which computes the eigenvalues of the reduced stiffness matrix K:

```
fK = sort( sqrt(eig(K)) / (2*pi) );
```

From this, the eigenfrequencies are obtained by taking the square root of the eigenvalues and dividing by 2π. The output is sorted in ascending order. The result should match the eigenfrequencies of the mode shapes that were added into the superelement (which can be found in the corresponding Sestra.lis file).

Similarly, the reduced mass (and stiffness) matrix can be verified using a line Matlab code, which computes the eigenvalues of the system of reduced stiffness matrix K and reduced mass matrix M:

```
fKM = sort( sqrt(eig(K,M)) / (2*pi) );
```

Again, the eigenfrequencies are obtained by taking the square root of the eigenvalues and dividing by 2π, after which the output is sorted in ascending order. The result of this should match the eigenfrequencies of the superelement, as listed in Table 5-1.

5.2 Verifying spatial convergence

The easiest way to verify spatial convergence is to run a (selection of) load case(s) on the reduced/superelement model. This can be done through Fatigue Manager by running the conversion for the selected load case(s). The conversion to Bladed will generate a wave load time history and structural analysis of this on the reduced model stored as R11.SIN in the load case folder. Similarly, the same analysis can be performed on the full model using the normal processing run, which will be stored as R1.SIN in the load case folder. Comparing the structural analysis results in both files gives an idea about how well the superelement model is spatially converged.

In this case, the displacement at the interface point has been compared between the full model when run in direct time integration and the superelement using a superelement conversion in the time domain including 40 modes. These displacements look very similar.

6 VERIFYING INTEGRATED MODEL CONVERSION

Some general information, as well as assumptions and limitations, regarding conversion of a Sesam model to Bladed for an integrated analysis are explained in this chapter.

6.1 Input

The model conversion from Sesam to Bladed is performed by Fatigue Manager. Reading in the Sesam FEM file (including the mesh of the structure and some basic hydrodynamic properties) and optionally a Wajac.inp file (including the hydrodynamic environment and additional hydrodynamic properties), the foundation model is converted into a Bladed .prj file.

The converter is available in Fatigue Manager via Conversions > Sesam to Bladed converter.

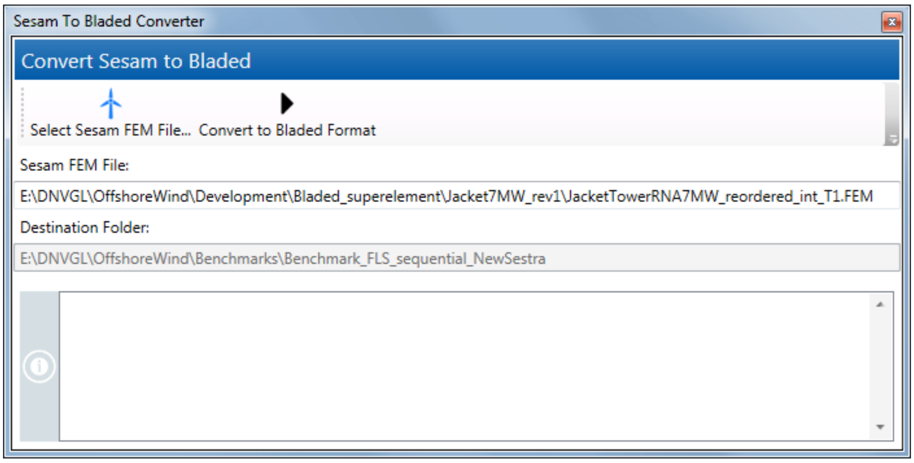


Figure 6-1 Converter of a Sesam model to Bladed in Sesam's Fatigue Manager.

6.2 Assumptions and limitations

A number of differences exist in modelling and analysis in Sesam and Bladed. Some of these result in assumptions and limitations related to the Sesam to Bladed converter, mostly due to the differences in modelling functionality between Sesam and Bladed. Besides points related to the converter, some other differences exist between Sesam and Bladed i.e. modelling and analysis assumptions. The known differences are summarised in this section.

6.2.1 General assumptions and limitations

6.2.1.1 Database units

To provide a correct conversion between Bladed and Sesam, the same database units should be used in both tools. Bladed uses SI units in its input fields. Therefore, the Sesam database should also be set to SI units (default) when creating a model to be converted to Bladed.

6.2.1.2 Simulation time length

If the simulation length in Sesam Fatigue Manager is set to 600s, the interface load files received from Bladed (for a superelement analysis) need to be 600s, while it might for example be only 599.95s (if a time step of 0.05s was used). The user needs to make sure that an additional time step is computed in Bladed.

6.2.2 Structure-related assumptions and limitations

6.2.2.1 Element types

Currently, the only elements converted from Sesam to Bladed are pipe section 2-noded (first order) beam elements. Non-cylindrical beams, plates and shells are currently not supported by the converter.

It is also possible to convert a model from Sesam to Bladed as a superelement. The superelement is then based on the Sesam model including all element types and can therefore include the effects of non-cylindrical beams, plates and shell elements.

6.2.2.2 Beam theory

Bladed uses Timoshenko beam theory, which includes element shear deformation. Sesam uses Euler-Bernoulli theory for 2-noded (first order) beam elements. By default, Euler-Bernoulli theory does not include shear deformation. However, an engineering factor on the beam section area is included in Sesam, which compensates for the lack of shear in the Euler-Bernoulli theory.

It should be noted that Sesam can use Timoshenko beam theory, but for 3-noded (second order) beam elements only. These are however not commonly used for beam structures in Sesam. Moreover, a drawback of using 3-noded beam elements is that they require meshing into smaller elements, while the 2-noded beam elements in Sesam do not need this since they include the theoretical element solution.

As part of the verification project, it was shown that the Timoshenko beams in Bladed give results that closely match those of the 2-noded 'extended' Euler-Bernoulli theory beam elements in Sesam, which is the default beam theory that is used in Sesam.

6.2.2.3 Beam end eccentricities

In Bladed, beam end eccentricities can be modelled by explicitly modelling additional nodes and stiff massless elements. In Sesam, this is not required as it is implicitly done inside the structural solver based on eccentricity values set during the modelling. As such, eccentricities are not straightforwardly converted from Sesam to Bladed. Currently, eccentricities are not converted from Sesam to Bladed.

Note that if eccentricities are required in the model, then the Bladed model can be manually adapted to include these. Alternatively, a superelement for Bladed can be converted from Sesam, which can be based on the Sesam model including eccentricities.

6.2.2.4 Tower top node

The tower top node in Bladed must be located at x=y=0. As such, the highest node in the Sesam model should also be at such a position. From this, the converter will select the node at the highest location in the model as the tower top node in Bladed. If desired, the node can be changed after opening the converted model in Bladed.

6.2.2.5 Point masses

Uniform point masses are converted from Sesam to Bladed. Generic point masses are currently not converted. If these are required, then it is possible to include them in a superelement for Bladed.

6.2.2.6 Boundary conditions

Boundary conditions are converted from Sesam to Bladed, including (equivalent linearized) spring matrices.

6.2.2.7 Geometric stiffening

Bladed by default includes geometric stiffening effects in the time domain structural analysis, as it enhances the accuracy of the tower dynamic response. Sesam has the possibility to include stress stiffening effects (a different name for the same effects), but only based on a single reference load case. For the purpose of comparing Bladed and Sesam, these effects should be disabled in both tools.

A free decay test in Bladed and Sesam can show the effects that the geometric stiffening option in Bladed has, see Appendix A.1 for further details.

6.2.2.8 Structural damping

Bladed and Sesam use different methods to apply structural damping to the tower / jacket. This is because Bladed calculates mode shapes for flexible structures, whereas Sesam retains all of the model's finite element degrees of freedom in the simulation.

- Bladed integrated model: Mode shapes are calculated for the combined tower / jacket structure, and damping is specified as percentage of critical damping per vibration mode.

- Sesam model: The finite element model's degrees of freedom are all retained. Rayleigh damping is typically used to include structural damping, although other methods are available as well.

- Bladed-Sesam superelement: The tower is modelled in Bladed, so uses critical damping per mode. The jacket is modelled in the superelement, which typically includes Rayleigh damping.

From Bladed 4.9, an improved damping method has been introduced in Bladed which can be used for both superelement and integrated modelling approaches. This allows the Rayleigh or modal damping of the complete support structure to be entered in Bladed, based on the support structure natural modes of vibration. From this input, Bladed will calculate corresponding damping for the superelement, tower and wind turbine parts in the model. This allows equivalent damping to be specified directly for the superelement and integrated modelling approaches in Bladed. This is discussed in Appendix C and further information is available in [3].

Bladed 4.8 can only accept modal damping as an input. However, in order to align damping between Bladed 4.8 and Sesam, it is desirable to enter modal damping in Bladed that is equivalent to Rayleigh damping. A method to calculate the necessary inputs in Bladed is described in Appendix B. Appendix A.1 demonstrates that the tower first mode damping is well aligned between Sesam and Bladed by using this method.

6.2.3 Hydrodynamic property-related assumptions and limitations

6.2.3.1 Morison coefficients

Both Bladed and Sesam allow Morison coefficients to be specified per beam element. Bladed does this per beam end (allowing linear variation over the beam), while in Sesam various ways of defining the Morison coefficients exist, either per beam or for multiple beams in one go (constant per beam, varying with beam diameter, roughness, wave direction or as computed by API rule).

Note that Sesam allows Morison coefficients to be specified perpendicular and longitudinal to the beam axis. Bladed also supports this functionality but it is not currently available through the Bladed GUI. Longitudinal coefficients (if specified) are therefore not converted to Bladed format, but can be added manually in Bladed through the Project Info screen if desired.

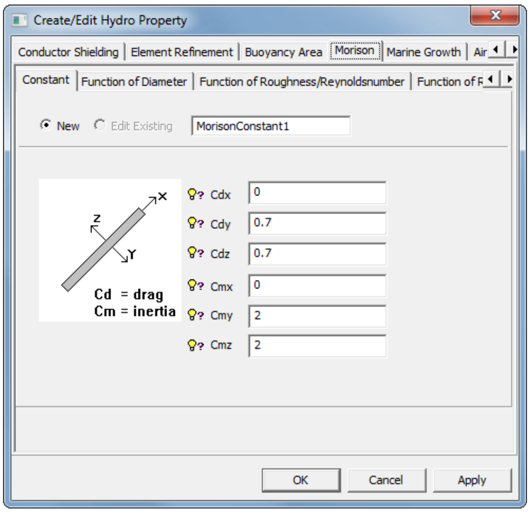


Figure 6-2 'Constant' Morison coefficient specification in Sesam's GeniE.

The converter currently only converts Morison coefficients specified using the 'Constant' Morison property specification in Sesam GeniE. These Morison coefficients are written to the T1.FEM file during meshing. The converter reads them from the T1.FEM file. It will currently not convert any Morison coefficient definitions on the Wajac.inp file.

6.2.3.2 Flooding

Flooding is available in both Bladed and Sesam. The conversion of these is as shown in Table 6-1.

Table 6-1 Conversion of flooded and unflooded elements from Sesam to Bladed

	Sesam	Bladed
Beam with internal water	Flooded element	Unsealed
Beam with internal air	Unflooded element	Sealed + unflooded

6.2.3.3 Marine growth

Marine growth in Bladed has a constant density for all members, and a thickness defined at each member end.

In Sesam, the specification of marine growth includes marine growth density, thickness and roughness, constant per element or defined as a function of height.

The differences in marine growth implementation in Sesam and Bladed make it hard to convert the marine growth such that it is identical in both tools, unless the user takes the differences in functionality into account in the specification of marine growth.

In case the marine growth is specified per member in Sesam, then the marine growth thickness will be the same in Bladed. If the specification in Sesam is specified per height, then the converter linearly interpolates the marine growth thickness at the beam end Z-coordinates and writes the interpolated thickness value to the member end in Bladed. In both cases, no roughness values can be converted to Bladed. The marine growth density for Bladed is taken as the average of the marine growth density factors in all specified marine growth properties/heights in Sesam, multiplied by the water density.

6.2.3.4 Wheeler stretching

Bladed includes Wheeler stretching of wave kinematics in the time domain. At the start of the verification study, Wheeler stretching was not yet available for irregular waves in the time domain in Sesam. Wheeler stretching was disabled in a special version of Bladed for the purposes of comparison in this study. However, it is not currently possible for Bladed users to disable Wheeler stretching using a released version of Bladed. The wave loads in sections 8.4 and 8.5 do therefore not include Wheeler stretching.

Wheeler stretching is now available in Sesam, from Wajac V7.1. The wave loads in section 8.6 therefore do include Wheeler stretching.

The effect of Wheeler stretching on interface loads is demonstrated in Appendix A.2.

6.2.3.5 Wave load calculation points

In Sesam, each member – or part of member below the free surface and above the mudline – is divided into at least two segments. The force intensities are calculated at the ends of each segment. These points are called load calculation points. This means that each member will have at least three wave load calculation points. The user can add additional wave load calculation points for further wave load calculation refinements.

Wave load calculation in Bladed is performed at each member end, i.e. only two points in each member. This means that the wave loads are computed with a lower resolution per member compared to Sesam.

In both Bladed and Sesam, there is always a calculation point at the sea surface or mudline.

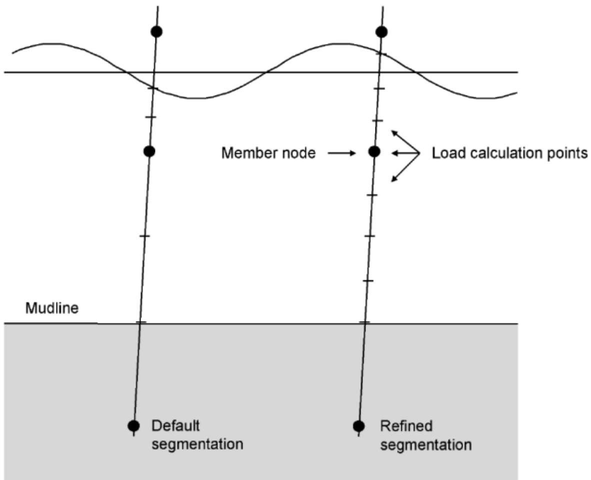


Figure 6-3 Member segmentation for wave load calculation points in Sesam's Wajac [4]

The user should be aware of the above when comparing wave loads and displacements of a model. The differences regarding wave load calculation points in Sesam versus Bladed may result in differences in the applied wave loading. If desired, additional members can be created in Bladed, either manually or by splitting concepts into multiple segments in Sesam and converting the model to Bladed. This will allow additional wave load calculation points in Bladed.

For this study, all of the Bladed support structure elements were divided into two elements compared to the Sesam model. This allowed the applied wave loading to be more equivalent between the two tools.

The beneficial effect of increasing the number of members in Bladed is demonstrated in Appendix A.3.

6.2.3.6 Reproducing irregular waves

In both Sesam and Bladed it is possible to generate time series of wave loading for irregular wave histories. These are based on random seeds. Because of this, the randomly generated wave history will differ between Sesam's Wajac and Bladed. In order to obtain an exact match in wave histories, the following possibilities exist:

- Export:

- It is possible to export the wave components that make up the irregular wave in Wajac by using the FCOMP command (available from Wajac V7.2). It is also possible to export the wave surface elevation.
- It is possible to export the wave surface elevation from Bladed.

- Import:
  - It is possible to read in a .SEA file in Bladed to reproduce an irregular wave. The .SEA file can be based on an FFT of a surface elevation (giving an approximate match) or on wave components (so that the exact irregular wave can be reproduced).
  - It is possible to use the SEAIN command in Wajac to reproduce an irregular wave. The SEAIN command can read a file containing a surface elevation (giving an approximate match) or wave components (so that the exact irregular wave can be reproduced).

The conversion from Sesam wave components to a Bladed .SEA file is explained in Appendix D.

6.2.3.7 Reproducing regular waves

Regular waves use the same wave theories in Sesam and Bladed. Since these do not use any random components, they can simply be reproduced by entering matching input data in both programs.

6.2.3.8 Reproducing constrained waves

Constrained waves are based on a random background wave with an embedded regular wave. Currently, it is not possible to create an exact match of such waves between Sesam and Bladed. There are two options:

- The first option is that the embedded wave can be matched when using Stream function in both programs. However, the (randomly generated) irregular background wave will not match.
- The second option is to use the surface elevation of the constrained wave from Sesam and use this in Bladed using a .SEA file (similar as in section 6.2.3.6). This will reproduce the complete wave in Bladed using Airy wave components, which may have a similar wave surface elevation but will have different water particle kinematics.

6.3 Verification

In order to verify the Sesam to Bladed converter for integrated foundation models, some example models were converted manually and compared with the corresponding models converted by the converter. This showed that the converter is properly converting the Sesam foundation model to Bladed, given the limitations and assumptions as outlined in section 6.2.

Besides this, resulting mass, natural frequencies, loads and displacements were compared for the model used in the verification study, as discussed in chapter 8.

7 VERIFYING INTERFACE AND MEMBER LOAD CONVERSION

The Bladed to Sesam converter can import member loads from Bladed, either for all members in the model (for an integrated analysis) or at a selected location such as the interface point (for a superelement analysis). Some example results were converted to Sesam and compared with the corresponding loads in Bladed. This showed that the converter is properly converting the Bladed loads to Sesam. From Bladed 4.8, interface loads for a superelement analysis are generated directly by Bladed in Sesam format.

Besides this, resulting loads and displacements were compared at the interface and certain locations in the jacket, as discussed in chapter 8.

8 RESULT COMPARISON

As part of the verification study, the mode shapes of the integrated structure in Sesam are compared to the superelement combined with the tower and RNA in Bladed. Besides that, loads, displacements and motions are compared at the interface as well as at some points in the jacket.

8.1 Masses

As a first check, the masses of the stand-alone jacket are compared in Sesam and Bladed for the different models involved.

The masses are listed in Table 8-1 and are identical in both tools.

Table 8-1 The masses in [kg] of the model in Sesam and Bladed.

Description	Sesam integrated	Bladed integrated
Jacket	1.15053E+06	1.36792E+06
Tower	2.17389E+05	
RNA	4.10000E+05	4.10000E+05
Total	1.77792E+06	1.77792E+06

8.2 Eigenmodes

In this section, the results of the eigenvalue analysis in Sesam and Bladed are compared for the stand-alone jacket and for the jacket with point mass RNA.

8.2.1 Stand-alone jacket

In order to make sure that the stand-alone jacket, both as a superelement and as an integrated model, are transferred properly from Sesam to Bladed, the eigenfrequencies of the systems are compared.

Table 8-2 contains the natural frequencies of the stand-alone jacket, 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:

- The superelement model in Sesam shows good spectral convergence with the full model of the stand-alone jacket in Sesam, with a maximum error of 0.50%.
- The full model of the stand-alone jacket in Bladed shows good agreement with the full model of the stand-alone jacket in Sesam, with a maximum error of 1.34%. Higher modes have larger errors (also beyond what is shown in Table 8-2). It should be noted that to find the coupled modes of the stand-alone jacket in Bladed, 50 uncoupled modes (degrees of freedom) have been used in the modal superposition[1]. As such, it is to be expected that the disagreement with the results of the Sesam model (which uses all degrees of freedom in the model, i.e. 1542) increases for higher modes. The results are understood to be adequate for a dynamic time domain analysis.
- The superelement model in Bladed shows good agreement with the superelement in Sesam, showing near-identical results for all modes. This is to be expected as Bladed is directly using the data provided by Sesam. Note that due to this, it is not relevant to compare the results of this case directly to the full model of the stand-alone jacket in Sesam, but only to the superelement in Sesam.

These comparisons show that the stand-alone jacket has been properly converted from Sesam to Bladed.

[1] Bladed 4.7 contains a limit of 50 uncoupled modes that can be used in the analysis. Bladed 4.8 does not have such a limit. Using more modes is expected to improve the comparison, which could be of interest for comparison purposes. Even though, it is understood that 50 modes is adequate for the analyses performed as part of this project.

Table 8-2 The natural frequencies of the stand-alone jacket for the full model and superelement (SE) model in Sesam and Bladed, up to a frequency of 10 Hz. (Full model frequencies in Sesam come from Table 5-1).

Mode	Sesam Freq. [Hz]	Sesam (SE) Freq. [Hz]	Sesam (SE) Error [%] vs Sesam	Bladed Freq. [Hz]	Bladed Error [%] vs Sesam	Bladed (SE) Freq. [Hz]	Bladed (SE) Error [%] vs Sesam	Bladed (SE) Error [%] vs Sesam (SE)
1	1.783	1.784	0.06 %	1.790	0.39 %	1.784	0.07 %	0.02 %
2	1.783	1.784	0.06 %	1.790	0.39 %	1.784	0.07 %	0.02 %
3	4.955	4.955	0.00 %	4.961	0.13 %	4.955	-0.01 %	-0.01 %
4	5.084	5.085	0.02 %	5.108	0.47 %	5.085	0.01 %	-0.01 %
5	5.365	5.369	0.07 %	5.373	0.14 %	5.369	0.08 %	0.00 %
6	5.365	5.369	0.07 %	5.373	0.14 %	5.369	0.08 %	0.00 %
7	6.177	6.177	0.00 %	6.188	0.18 %	6.177	0.01 %	0.01 %
8	6.425	6.425	0.00 %	6.446	0.33 %	6.425	-0.01 %	-0.01 %
9	6.592	6.592	0.00 %	6.598	0.09 %	6.592	0.00 %	0.00 %
10	6.945	6.980	0.50 %	6.963	0.26 %	6.980	0.50 %	-0.01 %
11	6.964	6.988	0.34 %	6.980	0.23 %	6.988	0.34 %	0.00 %
12	6.964	6.988	0.34 %	6.980	0.23 %	6.988	0.34 %	0.00 %
13	8.156	8.179	0.28 %	8.181	0.30 %	8.179	0.28 %	0.00 %
14	8.156	8.179	0.28 %	8.181	0.30 %	8.179	0.28 %	0.00 %
15	8.232	8.232	0.00 %	8.241	0.11 %	8.232	0.00 %	0.00 %
16	9.096	9.096	0.00 %	9.101	0.05 %	9.096	0.00 %	0.00 %
17	10.298	10.317	0.18 %	10.321	0.22 %	10.317	0.19 %	0.00 %
18	10.298	10.317	0.18 %	10.321	0.22 %	10.318	0.19 %	0.01 %
19	10.583	10.605	0.21 %	10.655	0.68 %	10.605	0.21 %	0.00 %
20	10.936	10.936	0.00 %	11.083	1.34 %	10.935	0.01 %	0.01 %

8.2.2 Stand-alone tower with RNA point mass

In order to make sure that the tower is modelled the same in Sesam and Bladed, the eigenfrequencies of the two systems are compared.

Table 8-3 contains the natural frequencies of the stand-alone tower with RNA point mass, in both Sesam and Bladed. The tower is considered to start from and have a fixed (clamped) boundary condition at the interface point. From the table it can be seen that although some differences exist, the frequencies are similar. These are considered adequate for the analyses to be performed as part of this project.

Table 8-3 The natural frequencies of the stand-alone tower with RNA point mass in Sesam and Bladed, for the first 10 modes.

Mode	Sesam Freq. [Hz]	Bladed Freq. [Hz]	Bladed Error [%]
1	0.330	0.329	-0.30 %
2	0.330	0.329	-0.16 %
3	3.732	3.724	-0.22 %
4	3.732	3.724	-0.22 %
5	7.277	7.277	0.00 %
6	10.776	10.703	-0.68 %
7	10.776	10.703	-0.68 %
8	14.645	14.646	0.01 %
9	20.861	20.614	-1.19 %
10	20.861	20.614	-1.19 %

8.2.3 Jacket with tower and RNA point mass

This section compares the frequencies of the model including jacket, tower and RNA point mass in Sesam and Bladed. For comparison purposes, the Sesam superelement is set up with a tower and RNA on it in Sesam, similar to how the Sesam superelement is used in Bladed. This is merely to compare the Bladed superelement case to Sesam.

Table 8-4 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. As for the stand-alone jacket, the difference in natural frequency increases for higher modes, but this should not pose a problem for the time domain analyses later on.
- The superelement model in Bladed shows similar results to both the full model in Sesam as well as the superelement model in Sesam.

These comparisons show that both the integrated model and superelement model are suitable for usage in the time domain to compare results between Sesam and Bladed.

Table 8-4 The natural frequencies of the jacket including tower and RNA point mass as full model or as superelement (SE) model in Sesam and the full model and superelement model in Bladed, up to a frequency of 10 Hz.

Mode	Sesam Freq. [Hz]	Sesam (SE) Freq. [Hz]	Sesam (SE) Error [%] vs Sesam	Bladed Freq. [Hz]	Bladed Error [%] vs Sesam	Bladed (SE) Freq. [Hz]	Bladed (SE) Error [%] vs Sesam	Bladed (SE) Error [%] vs Sesam (SE)
1	0.281	0.281	0.00 %	0.281	0.06 %	0.281	0.06 %	0.06 %
2	0.281	0.281	0.00 %	0.281	0.06 %	0.281	0.06 %	0.06 %
3	1.578	1.579	0.06 %	1.582	0.23 %	1.579	0.04 %	-0.03 %
4	1.578	1.579	0.06 %	1.582	0.23 %	1.579	0.04 %	-0.03 %
5	3.513	3.514	0.03 %	3.511	-0.07 %	3.508	-0.13 %	-0.16 %
6	3.513	3.514	0.03 %	3.511	-0.07 %	3.508	-0.13 %	-0.16 %
7	4.606	4.609	0.07 %	4.608	0.05 %	4.609	0.07 %	0.01 %
8	4.955	4.955	0.00 %	4.961	0.13 %	4.955	-0.01 %	-0.01 %
9	5.015	5.016	0.02 %	5.039	0.47 %	5.016	0.02 %	0.00 %
10	5.398	5.401	0.06 %	5.403	0.10 %	5.400	0.05 %	-0.01 %
11	5.398	5.401	0.06 %	5.403	0.10 %	5.400	0.05 %	-0.01 %
12	6.180	6.180	0.00 %	6.190	0.17 %	6.180	-0.01 %	-0.01 %
13	6.425	6.425	0.00 %	6.446	0.33 %	6.425	-0.01 %	-0.01 %
14	6.592	6.592	0.00 %	6.598	0.09 %	6.592	0.00 %	0.00 %
15	6.864	6.881	0.25 %	6.869	0.08 %	6.877	0.19 %	-0.05 %
16	6.864	6.881	0.25 %	6.869	0.08 %	6.877	0.19 %	-0.05 %
17	8.018	8.025	0.09 %	8.031	0.16 %	8.021	0.04 %	-0.05 %
18	8.018	8.025	0.09 %	8.031	0.16 %	8.021	0.04 %	-0.05 %
19	8.227	8.227	0.00 %	8.236	0.11 %	8.227	0.00 %	0.00 %
20	9.096	9.096	0.00 %	9.101	0.05 %	9.096	0.00 %	0.00 %
21	9.666	9.699	0.34 %	9.695	0.30 %	9.700	0.35 %	0.01 %
22	9.668	9.723	0.57 %	9.716	0.50 %	9.723	0.57 %	0.00 %
23	9.917	9.923	0.06 %	9.933	0.16 %	9.896	-0.21 %	-0.27 %
24	9.917	9.923	0.06 %	9.933	0.16 %	9.896	-0.21 %	-0.27 %
25	10.501	10.539	0.36 %	10.501	0.00 %	10.520	0.19 %	-0.18 %
26	10.501	10.539	0.36 %	10.501	0.00 %	10.520	0.19 %	-0.18 %
27	10.936	10.936	0.00 %	11.149	1.95 %	10.936	0.00 %	0.00 %

8.3 Sea surface elevation

The surface elevation is provided in the superelement reduced wave loads file. In Sesam, the wave loads are generated with a time step of 0.1s. Sesam linearly interpolates these from 0.1 to 0.05 seconds as input to the structural analysis (inside the structural analysis the loads are again interpolated to the internal calculation time step of 0.025 seconds). Bladed interpolates at the structural time step of 0.01s.

Typically for design analysis, the wave surface elevation will be generated in Bladed directly for an integrated run, or in Sesam for a superelement run. However, to compare the simulation results in Bladed and Sesam directly, it is necessary to have the same sea surface elevation in both tools.

For the original verification study (up to section 8.5), a Fast-Fourier Transform (FFT) is applied to the original Sesam sea surface to find the wave components. Note that this process is only possible for linear Airy waves. A Bladed SEA file is then generated based on the identified Fourier components, which is used in Bladed to attain the same surface elevation as used in Sesam. A 5Hz cut-off was used when generating the sea surface components in Sesam (the cut-off is automatically set to twice the wave calculation time step, i.e. 2x0.1s=0.2s, or 5Hz).

Another issue encountered relating to the FFT is that the sea surface time history in Sesam is non-periodic (non-repeating). However, the result of the time history generated from the FFT is periodic. This means that there will not be a perfect match between the original sea surface in Sesam and the recreated sea surface in Bladed. Differences in the sea surface time history are seen at the start and end of the time history, as shown in Figure 8-1. The Bladed sea surface matches the Sesam sea surface after 5s, although the transient differences in dynamic response of the turbine were found to last for around 30s.

For the later parts of the verification study (from section 8.6), the Sesam wave components are outputted and converted into a Bladed SEA file (see Appendix D for more info). This gives an exact match between the wave surface elevation and water particle kinematics in Sesam and Bladed.

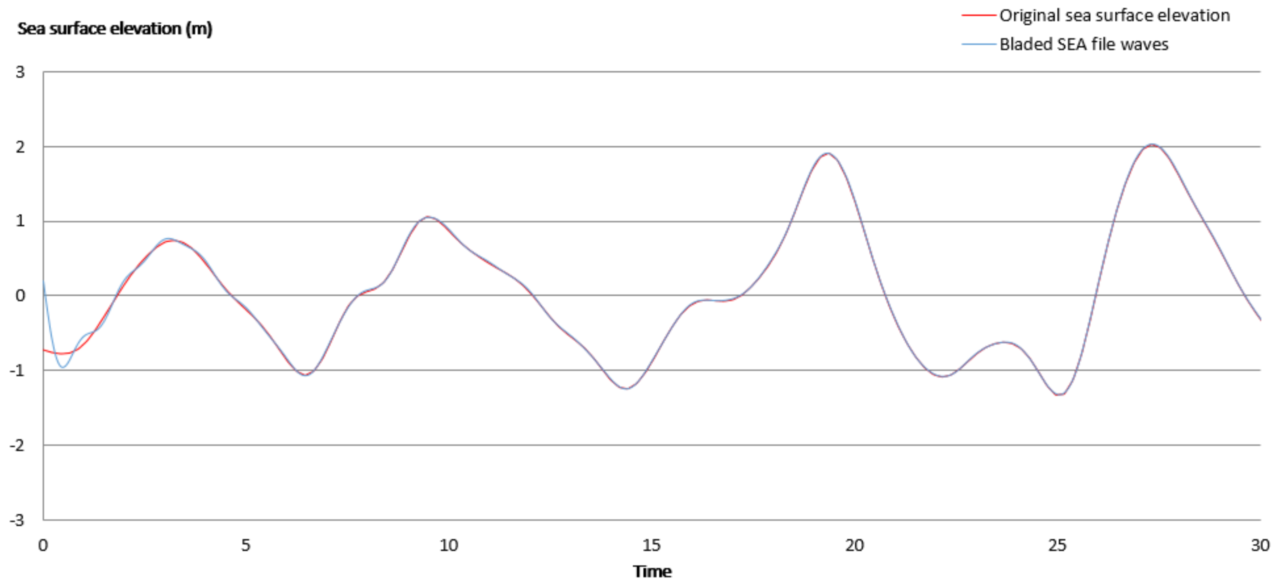


Figure 8-1 Comparison of provided wave surface elevation from Sesam (red) and as used in Bladed (blue).

8.4 Result comparison for model with point mass RNA and wave loading only

The loads and motion (displacement, velocity and acceleration) at the interface, selected jacket nodes and tower top are compared between the different analysis types in Bladed and Sesam. The applied loads are as specified in section 3.3, i.e. gravity and a wave load is applied to the model, but no wind loading is applied. The RNA of the turbine is modelled as a point mass. To be able to have a clear comparison between the results of the different runs, the results are inspected for a short time interval from 50 to 70 seconds. Results before 50 seconds are truncated due to possible start-up transients (this is supposed to be conservative, shorter truncation times are most likely possible).

Damping is applied to the jacket and tower in both Sesam and Bladed. However, the application of damping is different in both tools. The applied damping is as follows:

- Sesam integrated: Rayleigh damping is applied, made up of 0.02 (2%) times the reduced stiffness matrix and the reduced mass matrix.
- Sesam superelement: Same as for the Sesam integrated model, used in the reconstruction run when using the interface loads from Bladed.
- Bladed integrated: Modal damping is applied to the integrated jacket model. Damping ratios were calculated to be equivalent to Rayleigh damping in Sesam using the method explained in Appendix B.
- Bladed superelement: The jacket contains a damping matrix made up of 2% Rayleigh damping relative to the stiffness and mass matrices. On the tower, modal damping was applied, again using the method from Appendix B.

8.4.1 Interface loads and motion due to wave loading

The results of the interface loads and motion are discussed in the following subsections.

8.4.1.1 Interface loads

The interface loads are displayed in Figure 8-2. The interface loads of the Sesam integrated and Bladed run using the Sesam superelement are very similar. Loads in F_x and M_y are dominating, which matches the applied wave loading in x-direction. The results of the superelement response run in Sesam, which uses the Bladed superelement interface loads, are virtually identical to those of the Bladed superelement interface loads. This is as expected for the interface loads, since the resulting Bladed superelement interface loads are applied at the interface in Sesam.

The Bladed integrated run shows similar results, but shows a bit more variation which is particularly visible around 59 seconds in Figure 8-2. This is understood to be due to the differences in modelling, damping and analysis, which were described in section 6.2.

Although some differences between Sesam and Bladed can be seen, the trend of the interface loads is similar and considered close enough for the comparison. It should be noted that in a normal workflow one will use either Sesam or Bladed for calculation of wave loads, thereby removing some of the limitations that were imposed on this comparison to match the modelling assumptions in both tools.

It should be noted that the jacket model in the Bladed integrated run contains twice as many elements as that in the Sesam integrated model. This has been done to improve the comparison between the calculated wave loads, due to differences in the wave load computation methods in Sesam and Bladed. For more information on this, see Appendix A.3.

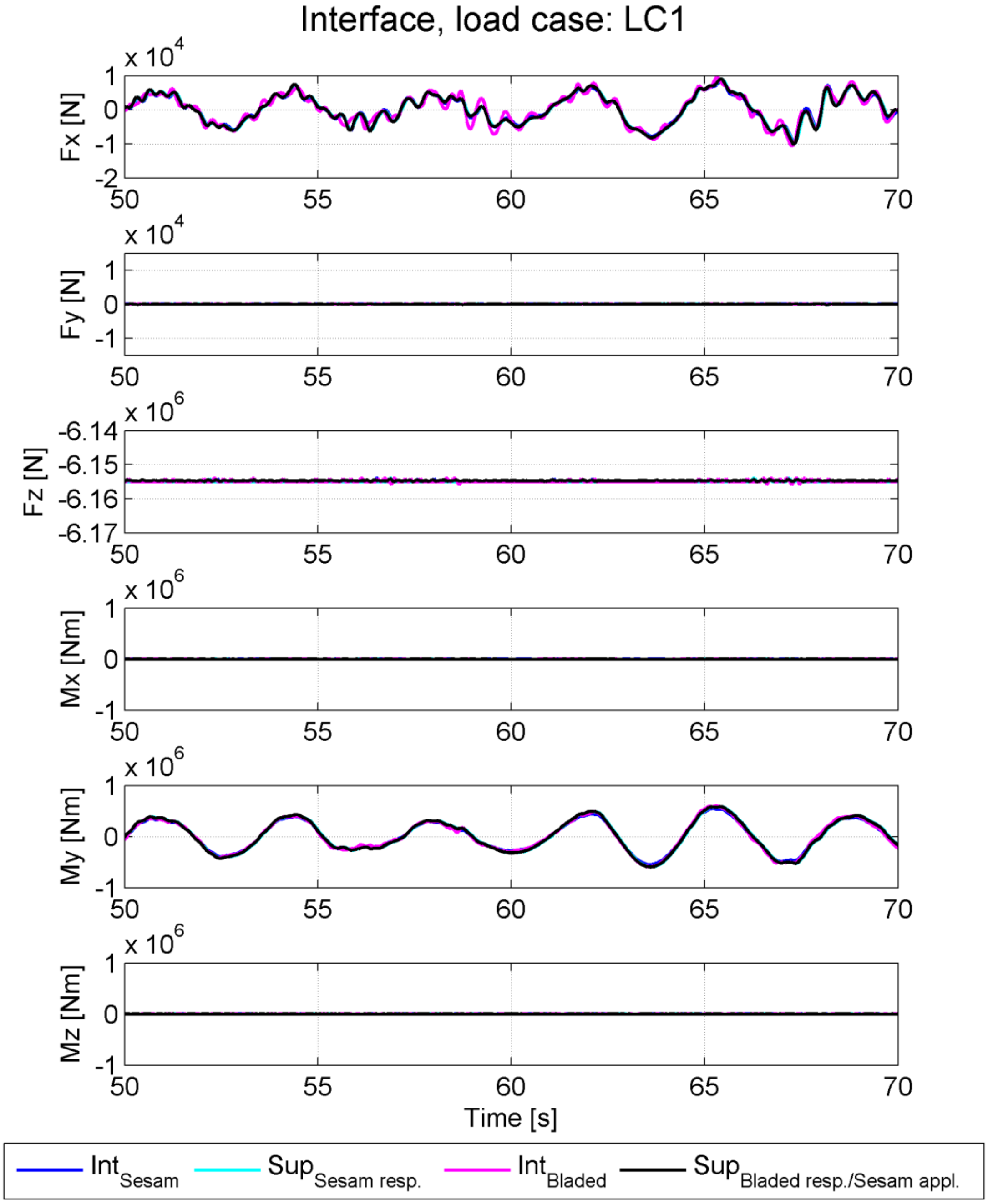


Figure 8-2 Loads at the interface over the first 20 seconds time period.

8.4.1.2 Interface displacements

The resulting displacements are visualized in Figure 8-3. The results of Bladed and Sesam are nearly identical. Similarly as for the loads, a little more variation is seen for the Bladed integrated model, but these differences are minor. No significant sideways motion are present, which matches the applied loading.

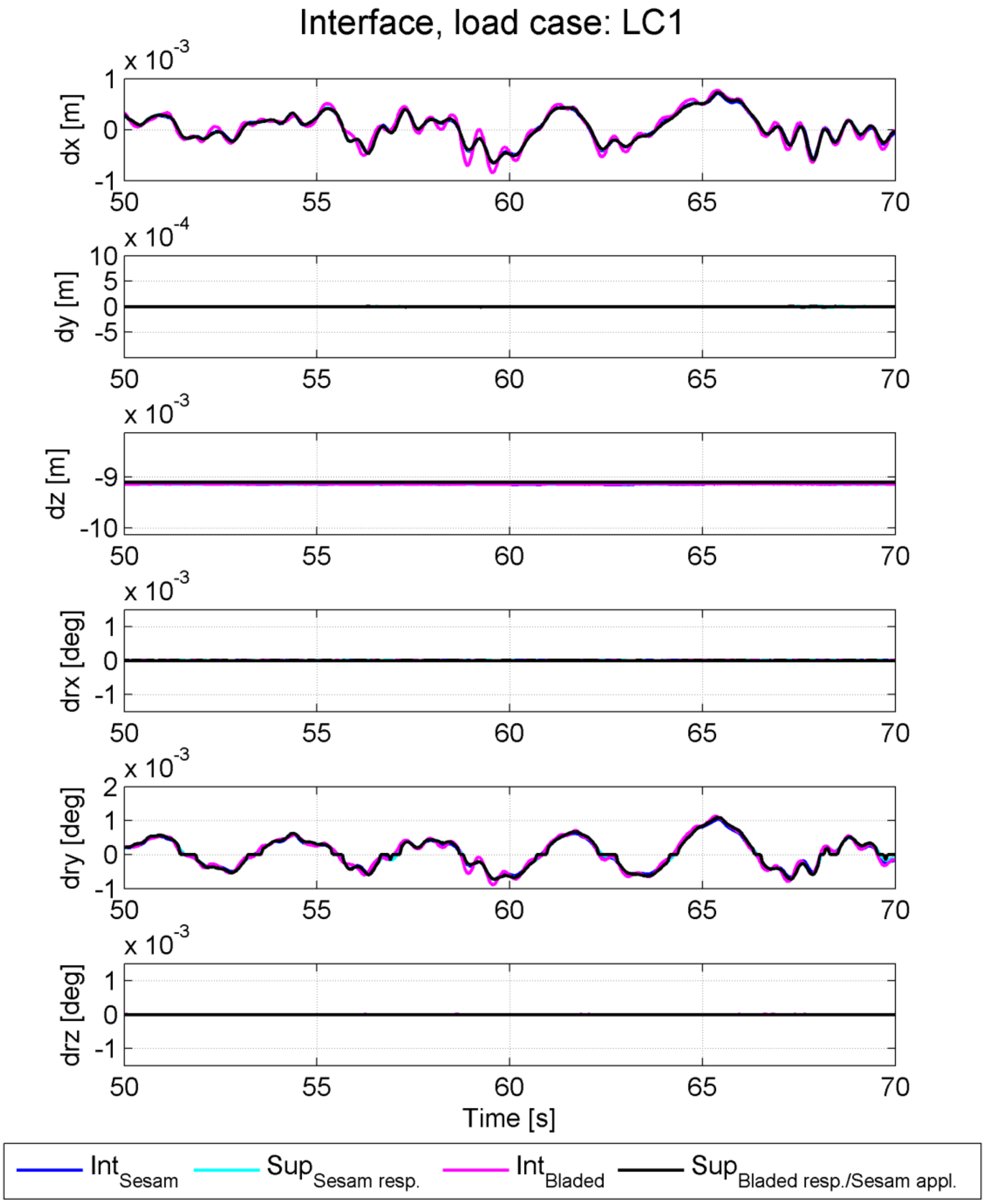


Figure 8-3 Displacements at the interface over the first 20 seconds time period.

8.4.1.3 Interface velocities

The resulting velocities are visualized in Figure 8-4. Again, the results of Bladed and Sesam are nearly identical. The Bladed integrated model again shows some larger peaks and troughs, while the other three signals are very close to each other.

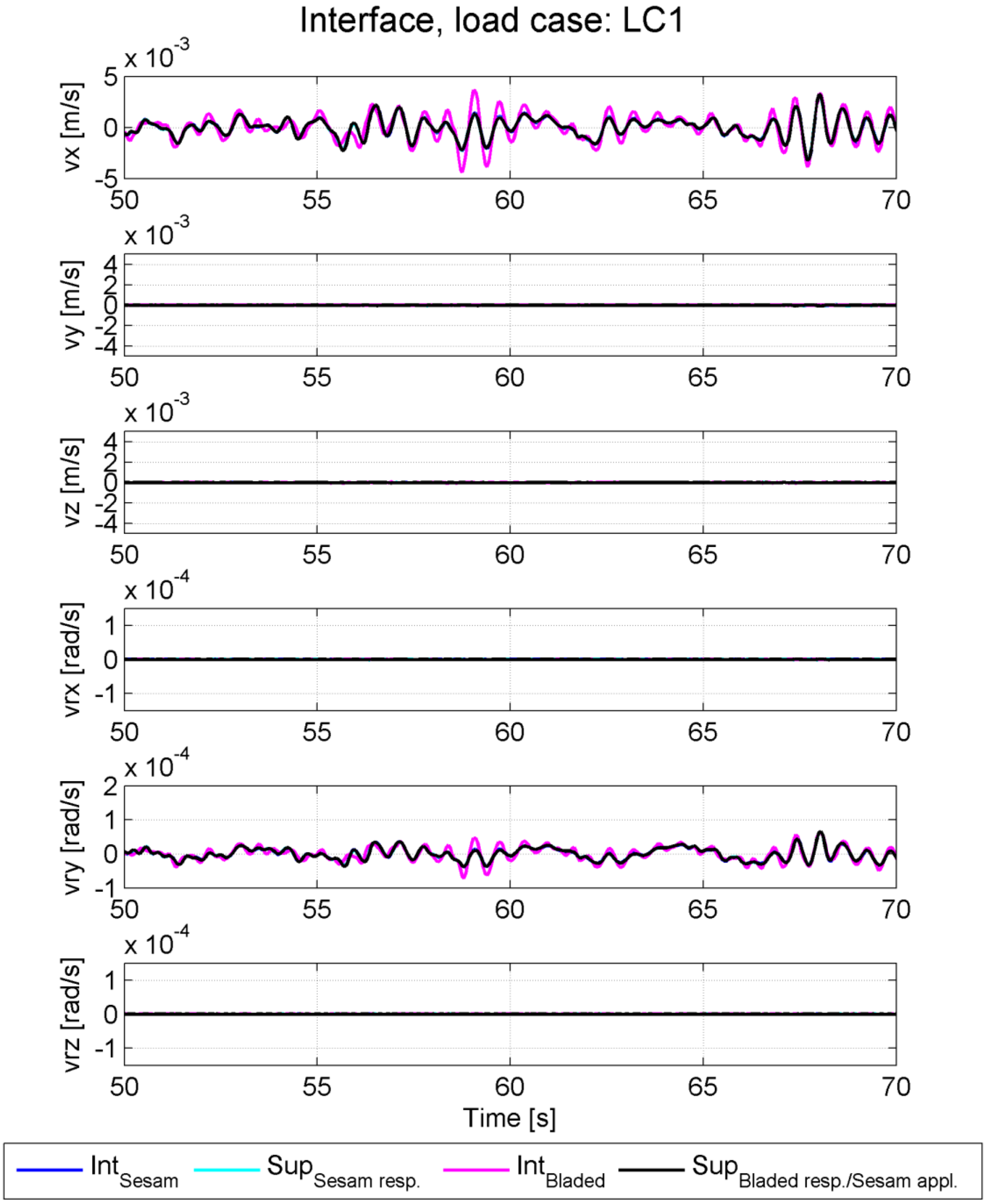


Figure 8-4 Velocities at the interface over the first 20 seconds time period.

8.4.1.4 Interface accelerations

The resulting accelerations are visualized in Figure 8-5. As for the interface loads, displacements and velocities, the different methods compare quite well. Again, the Bladed integrated model shows more fluctuation, which is more pronounced for the acceleration than for the loads and displacements.

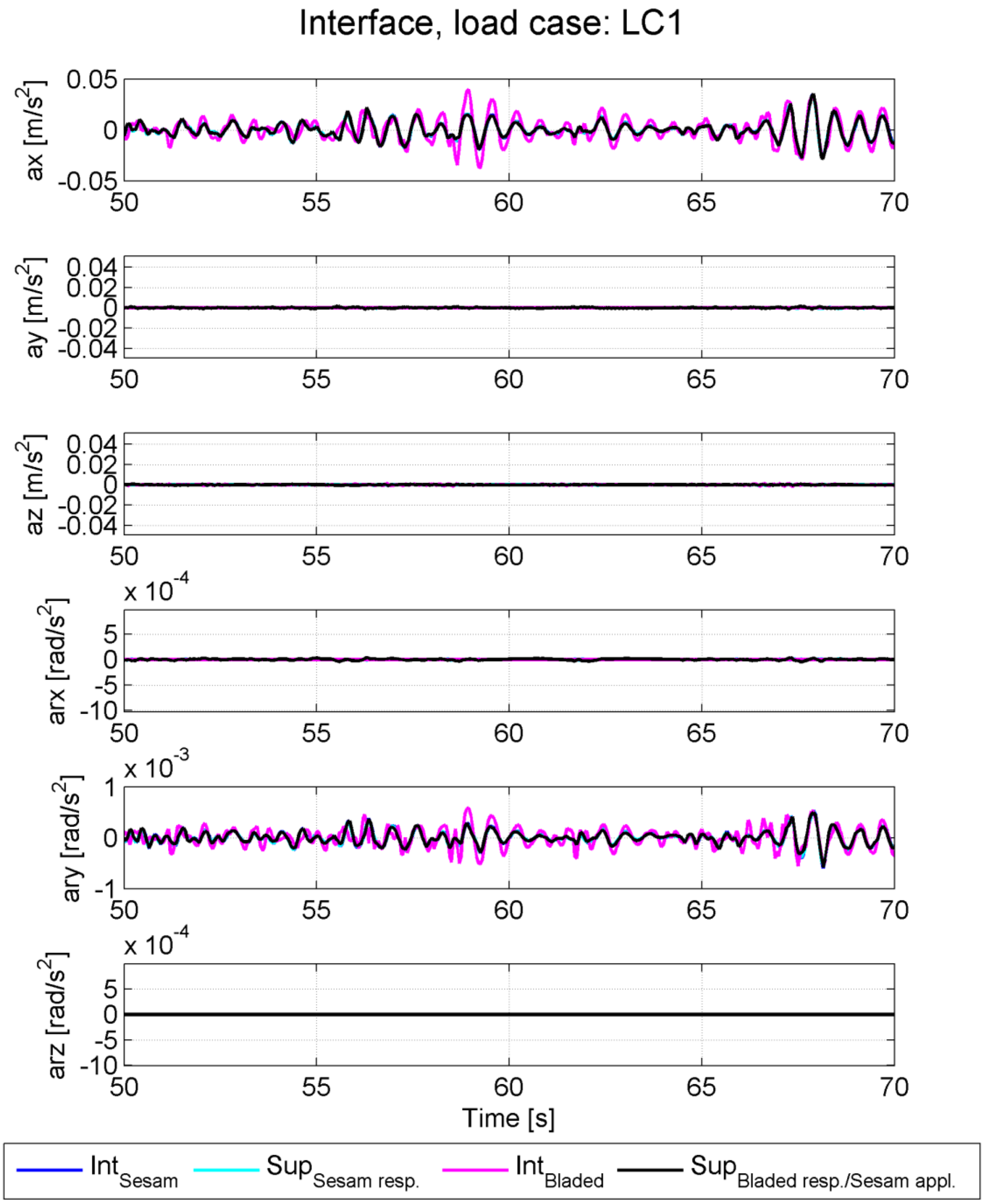


Figure 8-5 Accelerations at the interface over the first 20 seconds time period.

8.4.2 Jacket displacements due to wave loading

A comparison is performed for the displacements at other points in the jacket. The displacements are extracted from three analyses, being the Sesam integrated analysis, the retracking run in Sesam (which uses the interface loads obtained from the superelement analysis in Bladed) and the integrated Bladed analysis. No Bladed superelement results are included. This is because the superelement run in Bladed does not have the actual jacket present, but instead only the superelement matrices are there. As a result, no displacement values can be extracted. This is inherent to the superelement methodology and one of the reasons why the superelement run requires a retracking run using the wave loads and interface loads in Sesam afterwards.

The wave that is modelled in the simulations is running along the x-axis in the positive direction of the global coordinate system. The displacements have therefore been extracted at joints on the negative x-side of the model, i.e. on the side of the jacket that sees the incoming wave first. Two joints are selected near the top of the jacket (one K-joint and one X-joint) and two near the bottom of the jacket. The positions are indicated in Figure 8-6.

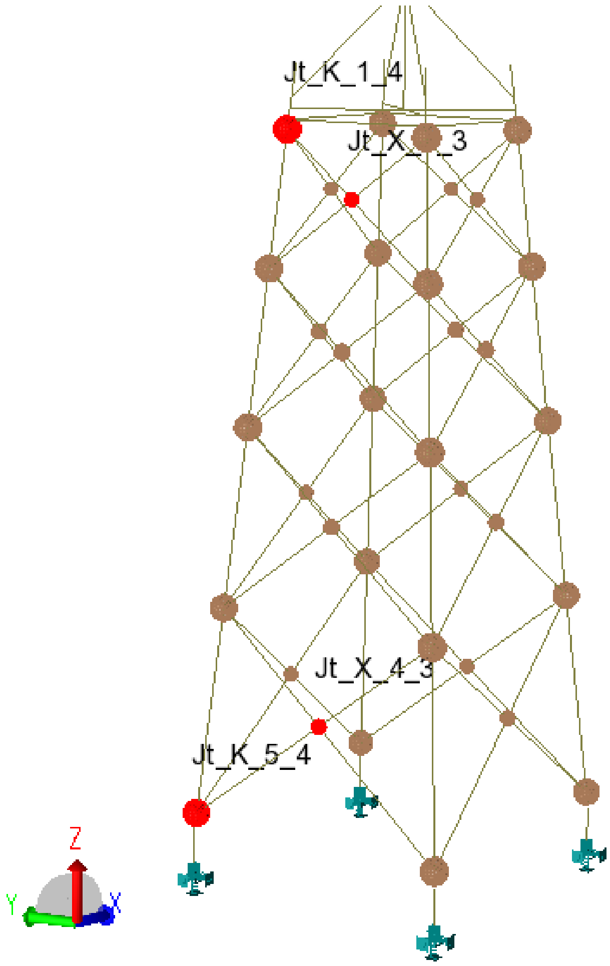


Figure 8-6 Positions (highlighted in red) at which the displacements are compared between the different analyses. These are on the side of the jacket that will 'see' the wave first.

In Figure 8-7 to Figure 8-10 the jacket displacements are shown. It can be seen that in general the variation matches well between the Sesam integrated and Sesam+Bladed superelement analysis. Similarly as at the interface, the fluctuations of the Bladed integrated analysis are slightly larger. This difference is mainly noticeable in the displacement in x-direction (main loading direction) and the rotation around the y-axis (around the horizontal axis perpendicular to the main loading direction), as well as for the vertical direction (dz), and is visible for all four joints. The cause might be that the damping is applied using different methods in Bladed and Sesam and/or other inherent differences between the modelling and analyses in Sesam and Bladed. Overall though, the displacements and rotations at the joints are comparable.

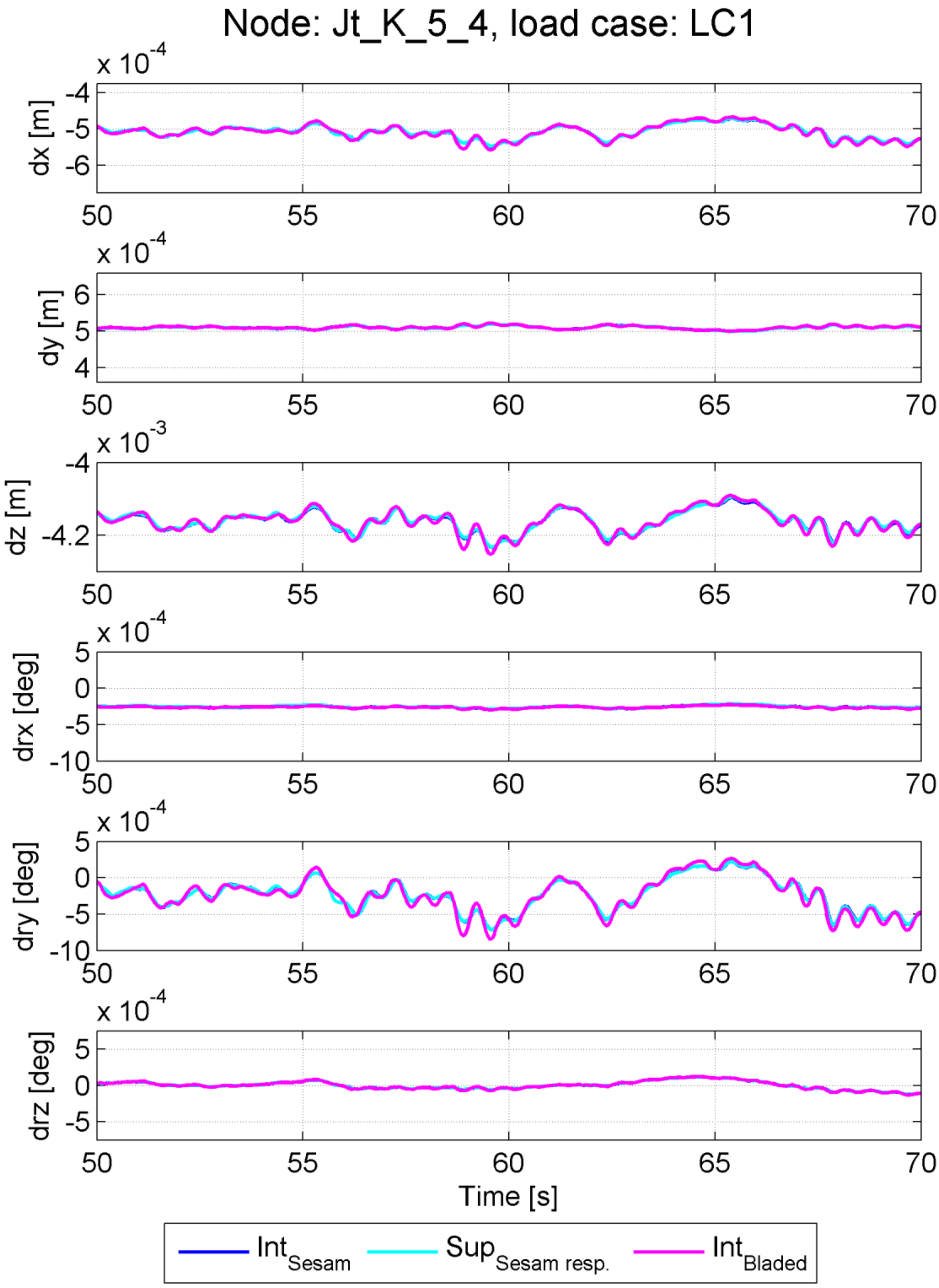


Figure 8-7 Displacement and rotation at joint Jt_K_5_4 over the first 20 seconds time period.

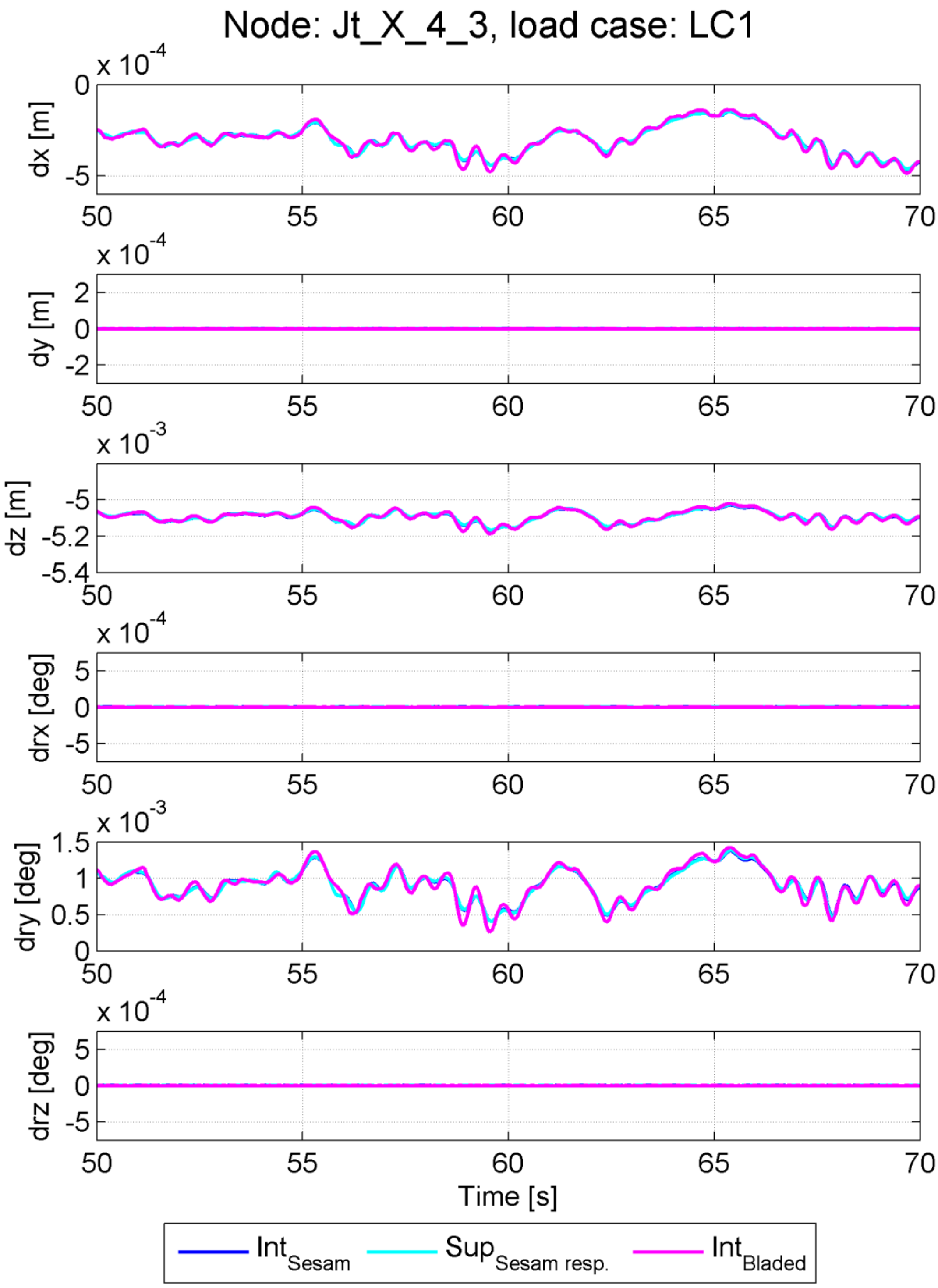


Figure 8-8 Displacement and rotation at joint Jt_X_4_3 over the first 20 seconds time period.

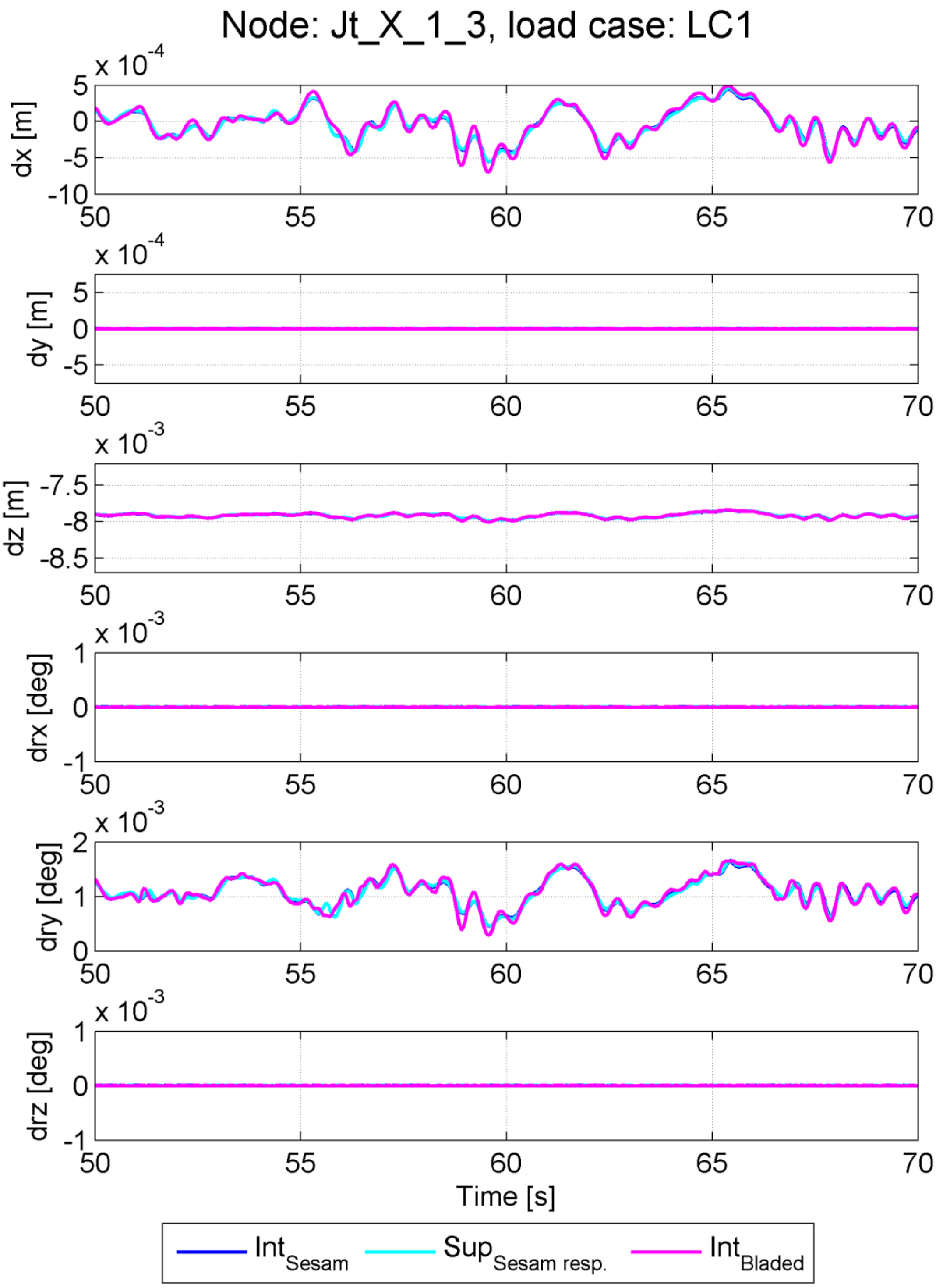


Figure 8-9 Displacement and rotation at joint Jt_X_1_3 over the first 20 seconds time period.

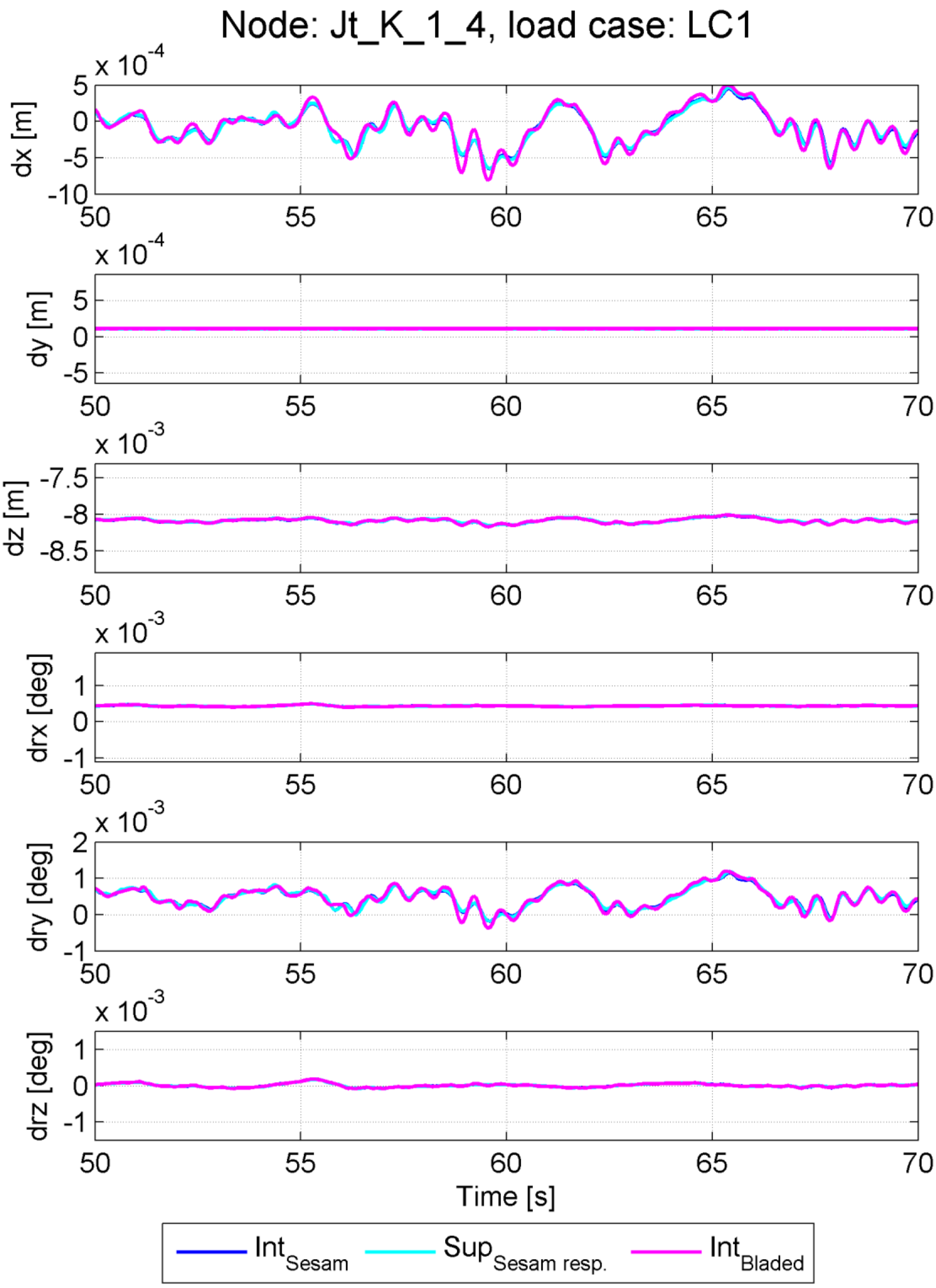


Figure 8-10 Displacement and rotation at joint Jt_K_1_4 over the first 20 seconds time period.

8.4.3 Tower top motions due to wave loading

In addition to results at the interface and at the jacket joints, the motions at the tower top are compared. These should give a good indication on how well the different models compare. 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. Results that compare well at the tower top should therefore give a good indication on how closely the system has been modelled in the different ways.

The tower top displacements are shown in Figure 8-11. The Sesam integrated and Bladed integrated model include the tower, point mass RNA and jacket in a single model, whereas the superelement model is a combination of the Sesam superelement combined with the tower and point mass RNA in Bladed. The displacements compare well, and no significant differences are seen. Some fluctuation is visible for the rotation around the main loading direction (dry) in the Bladed integrated model, which might explain the differences observed at the interface and lower in the jacket as observed in previous sections.

For the tower top velocities, shown in Figure 8-12, the results are similar as for the displacements, i.e. good agreement is seen between the different systems. For the rotational velocity around the main loading direction (vry) some more fluctuation is seen.

Figure 8-13 displays the tower top accelerations. The fluctuations in acceleration for the Bladed integrated model are more pronounced here for the rotational acceleration around the main loading direction (ary). Besides that, fluctuation in the accelerations in the main loading direction (ax) and vertical direction (az) become apparent too. Overall though, the impact of these fluctuations on the displacement is minor.

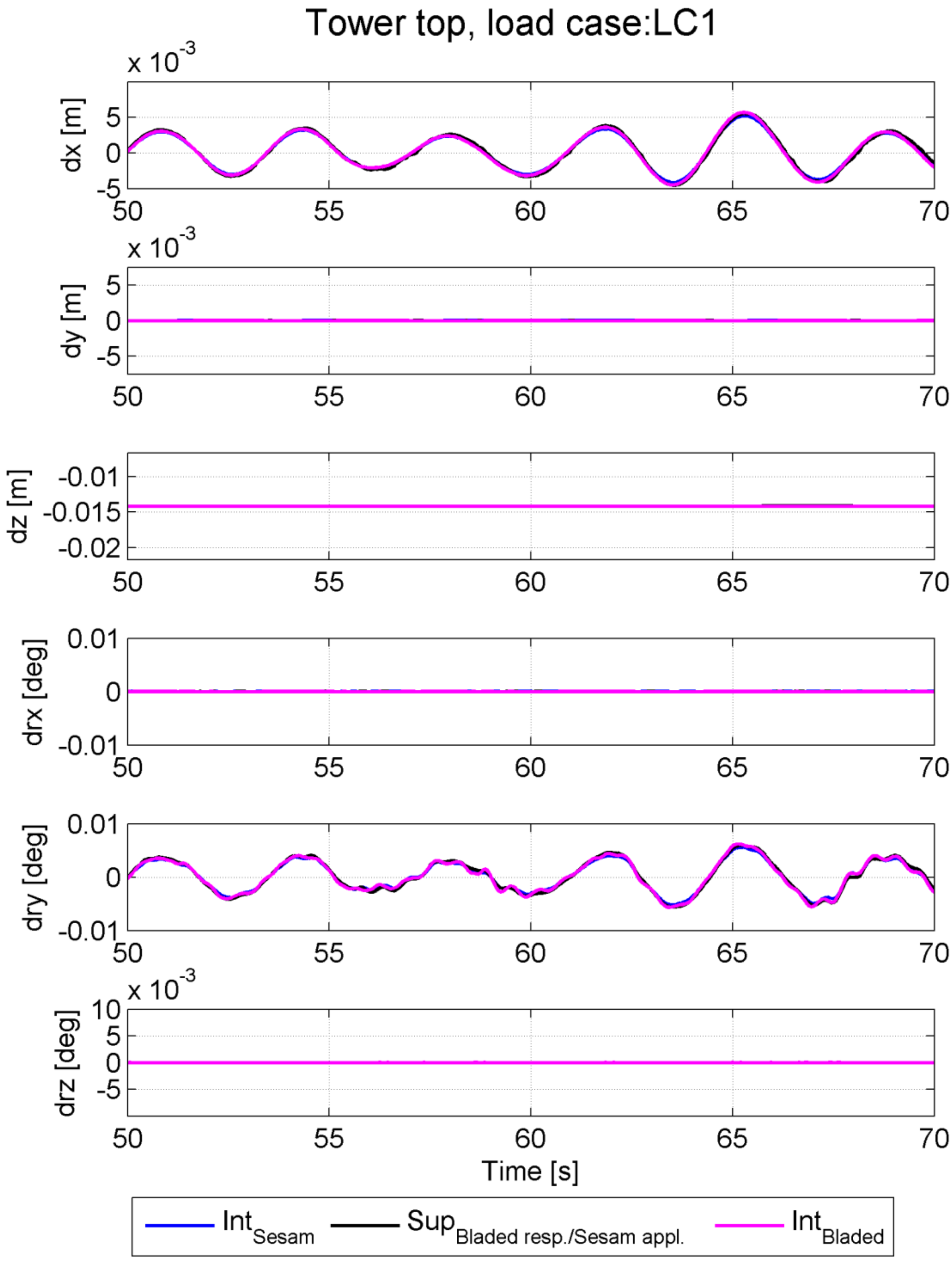


Figure 8-11 Displacements at the tower top over the first 20 seconds time period.

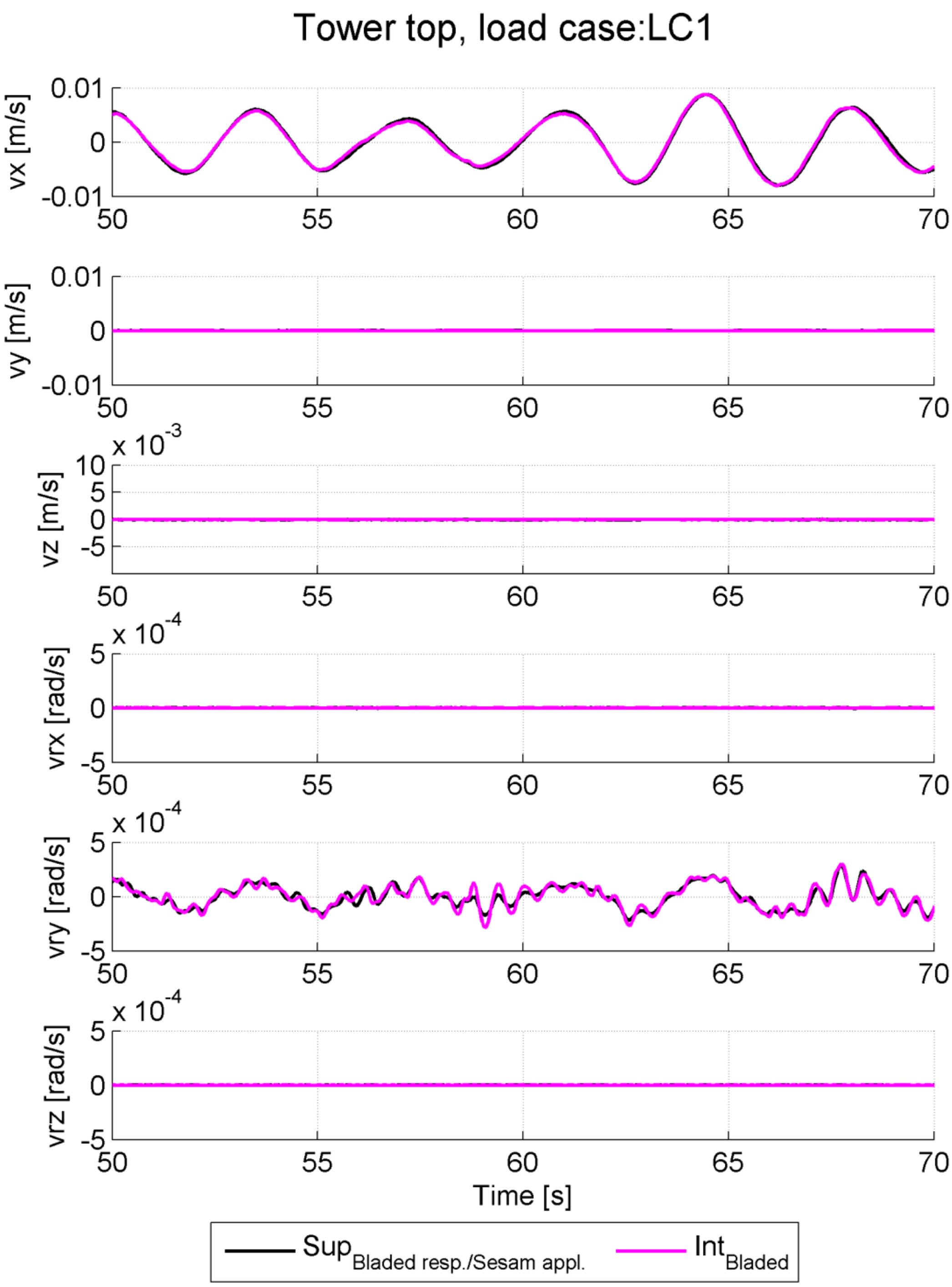


Figure 8-12 Velocities at the tower top over the first 20 seconds time period.

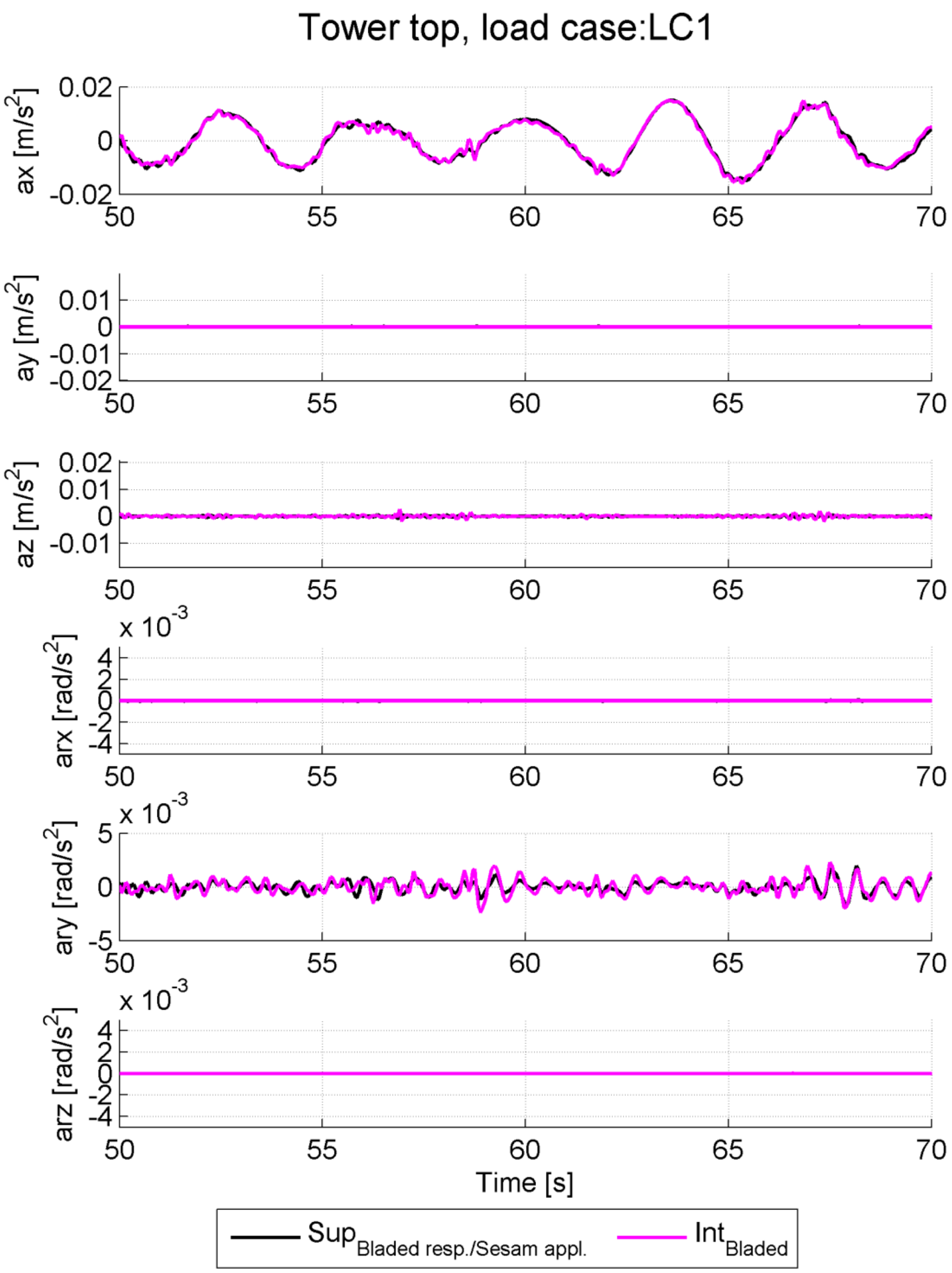


Figure 8-13 Accelerations at the tower top over the first 20 seconds time period.

8.5 Result comparison for model with wind turbine under combined wave and wind loading

In section 8.4 the different analyses were compared for wave loading only and with a point mass RNA. In this section, the point mass RNA has been replaced with a wind turbine model in Bladed. The same wave loading is applied to the jacket and wind loading is applied to the wind turbine in addition. Note that in this case, no Sesam integrated run is included in the result comparison, since a wind turbine rotor cannot be modelled in Sesam.

Since the RNA point mass has been replaced by the actual rotor-nacelle assembly model, the natural frequencies for the tower are now different, as the RNA has full mass and inertia properties rather than a simple point mass. Therefore, the damping of the tower has been re-tuned, both for the superelement and integrated model.

8.5.1 Interface loads and motion due to wave and wind loading

The resulting loads, displacements, velocities and accelerations at the interface are shown in Figure 8-14 to Figure 8-17. As for the case with a point mass RNA and no wind loading (see section 8.4), the superelement analysis results from Bladed and Sesam are near identical. This confirms the correct implementation of the superelement and loads conversion from Sesam to Bladed and vice versa for the interface loads, as well as enough modes being included in the superelement used in this verification study. The integrated analysis results from Bladed match closely to the superelement results as well.

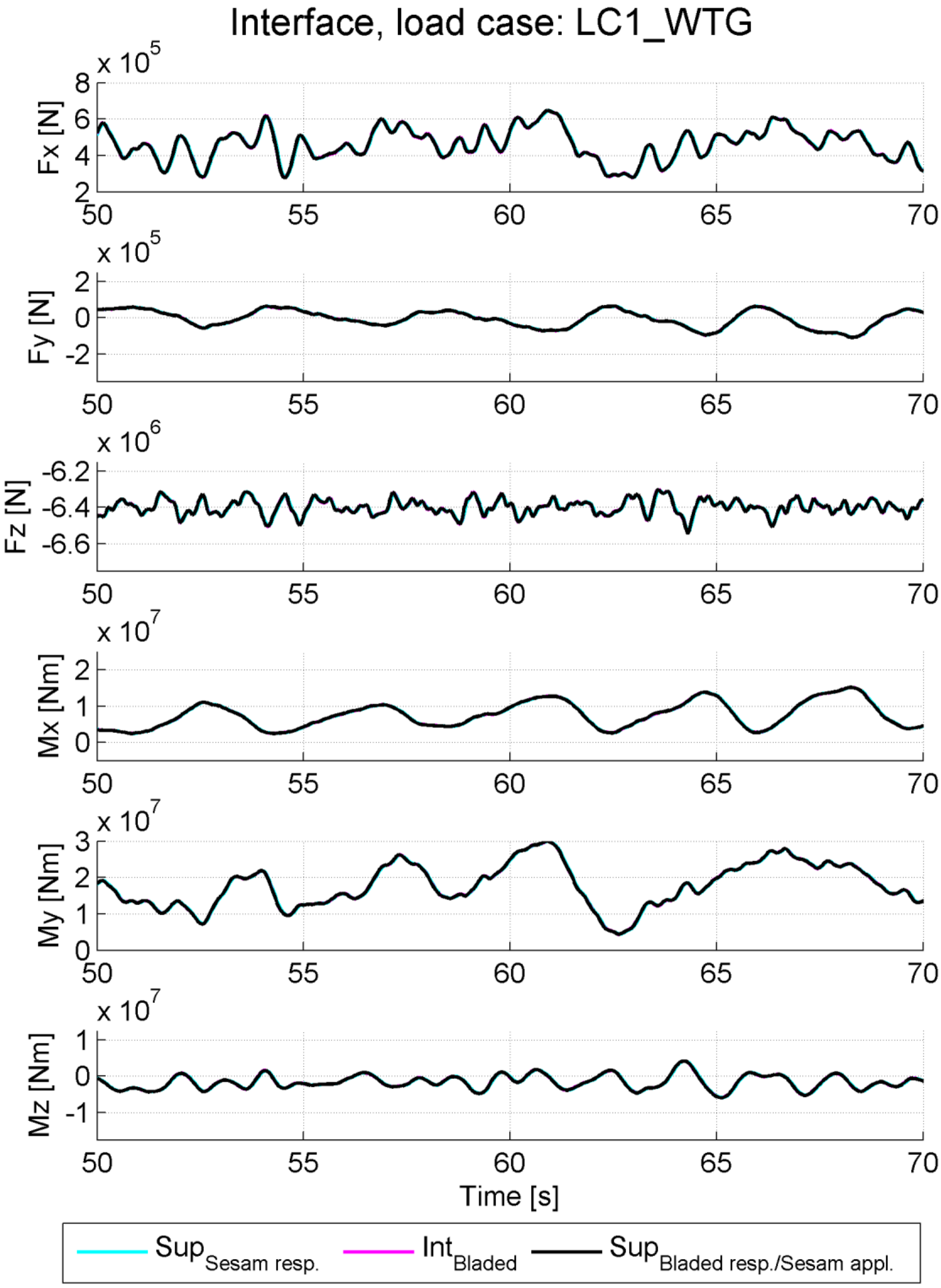


Figure 8-14 Loads at the interface over the first 20 seconds time period for model with wind turbine.

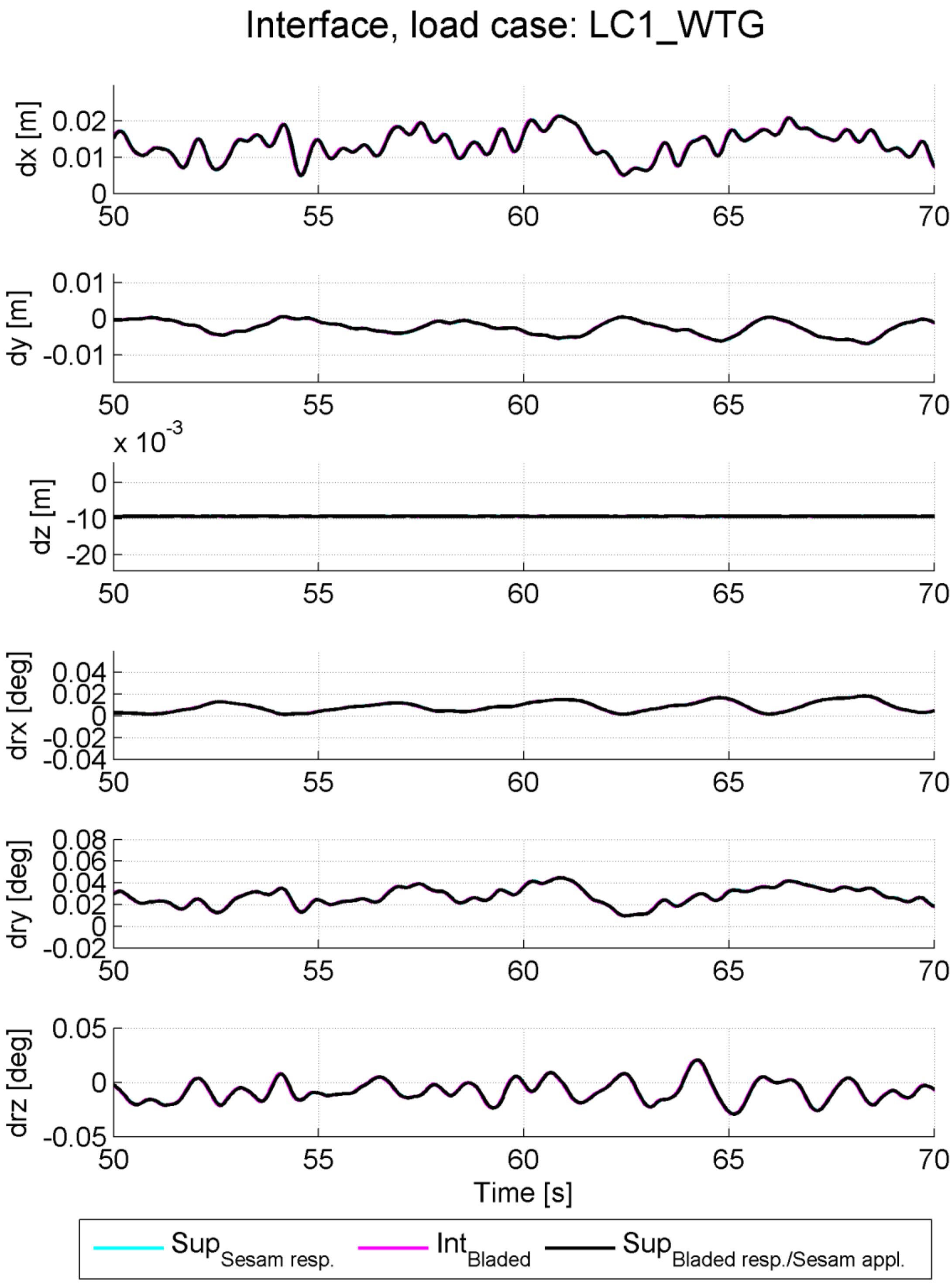


Figure 8-15 Displacements at the interface over the first 20 seconds time period for model with wind turbine.

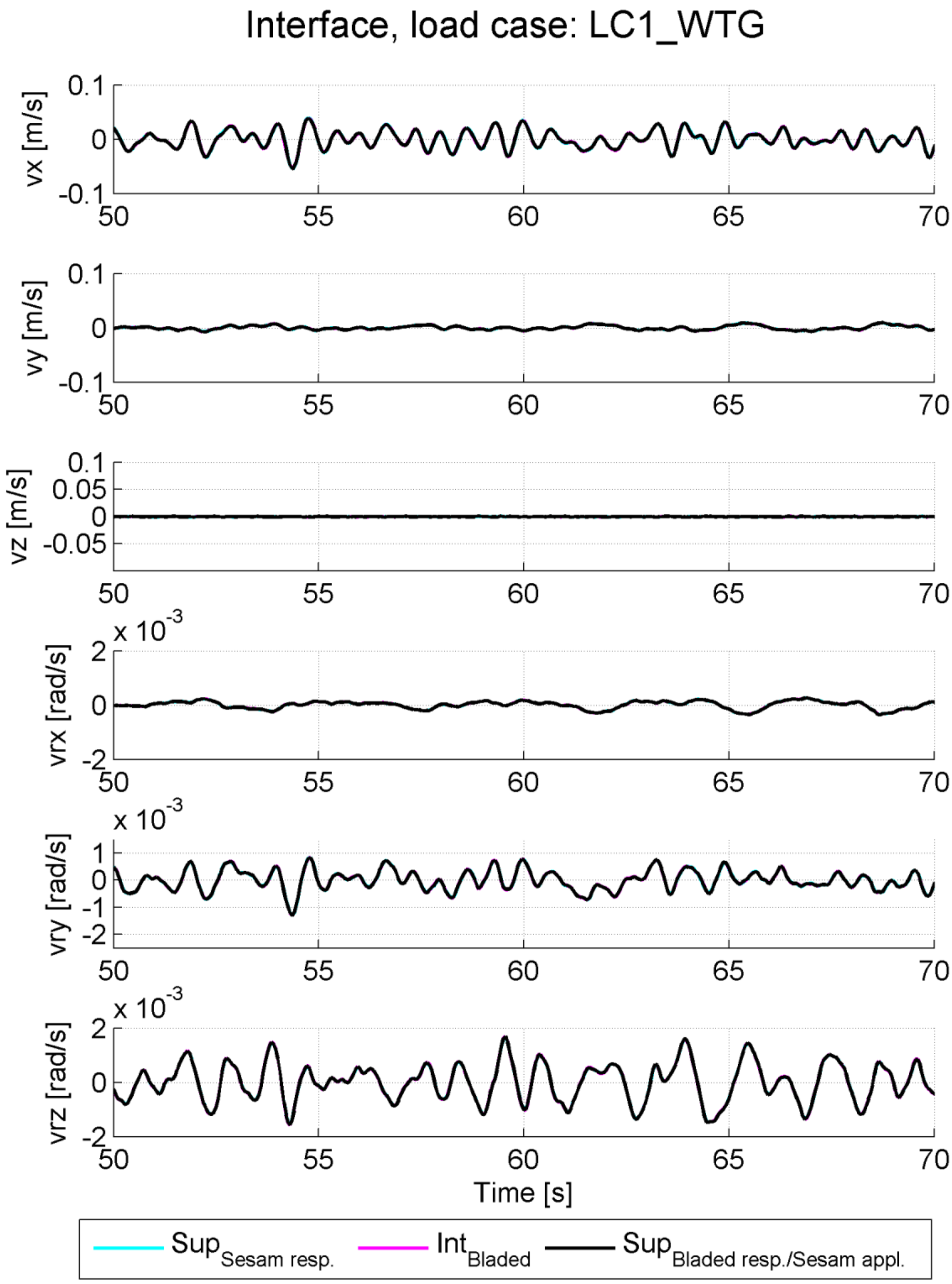


Figure 8-16 Velocities at the interface over the first 20 seconds time period for model with wind turbine.

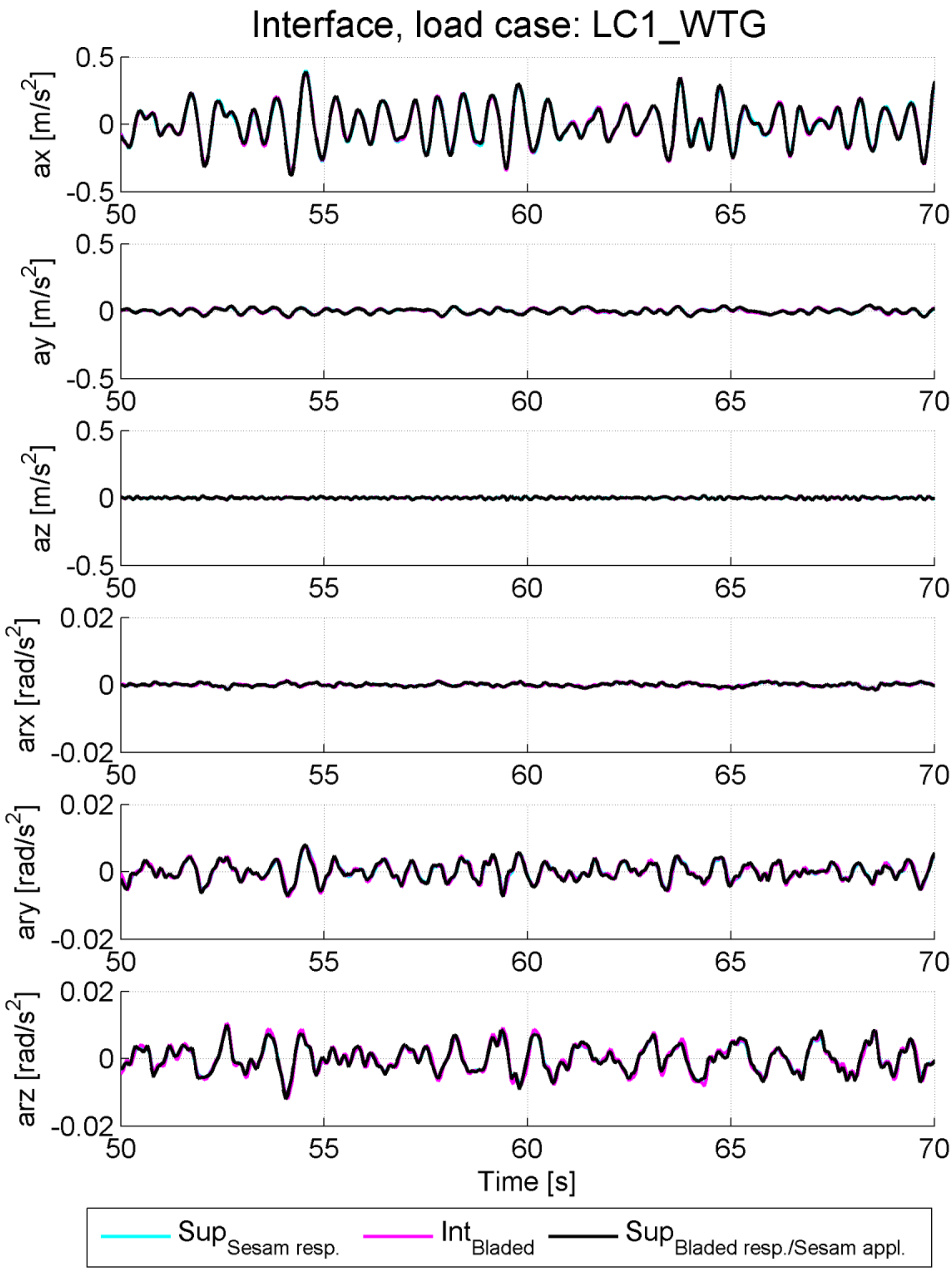


Figure 8-17 Accelerations at the interface over the first 20 seconds time period for model with wind turbine.

8.5.2 Jacket displacements due to wave and wind loading

Displacements are compared for the same joints in the jacket as in section 8.4.2, see Figure 8-6. The displacements are extracted from two analyses, being the retracking superelement run in Sesam (which uses the interface loads obtained from the superelement analysis in Bladed) and the integrated Bladed analysis. No Sesam integrated run is included, because a turbine cannot be included in Sesam, and no Bladed superelement results are included, because the superelement run in Bladed does not have the actual jacket present.

The wave and wind that are modelled in the simulations are running along the x-axis in the positive direction of the global coordinate system. The displacements have therefore been extracted at joints on the negative x-side of the model, i.e. on the side of the jacket that sees the incoming wave and wind first. Two joints are selected near the top of the jacket (one K-joint and one X-joint) and two near the bottom of the jacket. The positions are indicated in Figure 8-6.

The jacket displacements are shown in Figure 8-18 to Figure 8-21. The results of the integrated and superelement analysis can be seen to be near-identical.

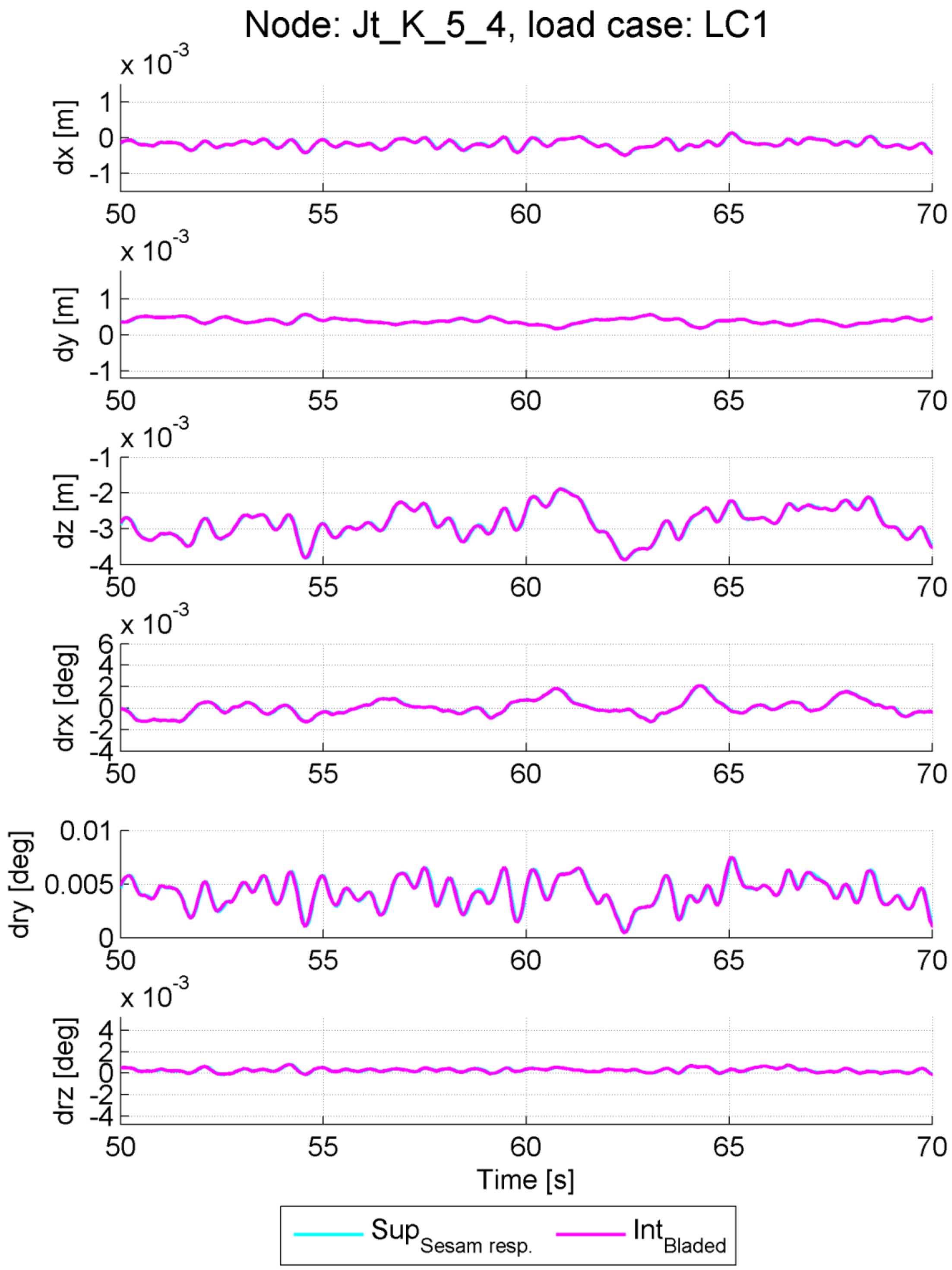


Figure 8-18 Displacement and rotation at joint Jt_K_5_4 over the first 20 seconds time period for model with wind turbine.

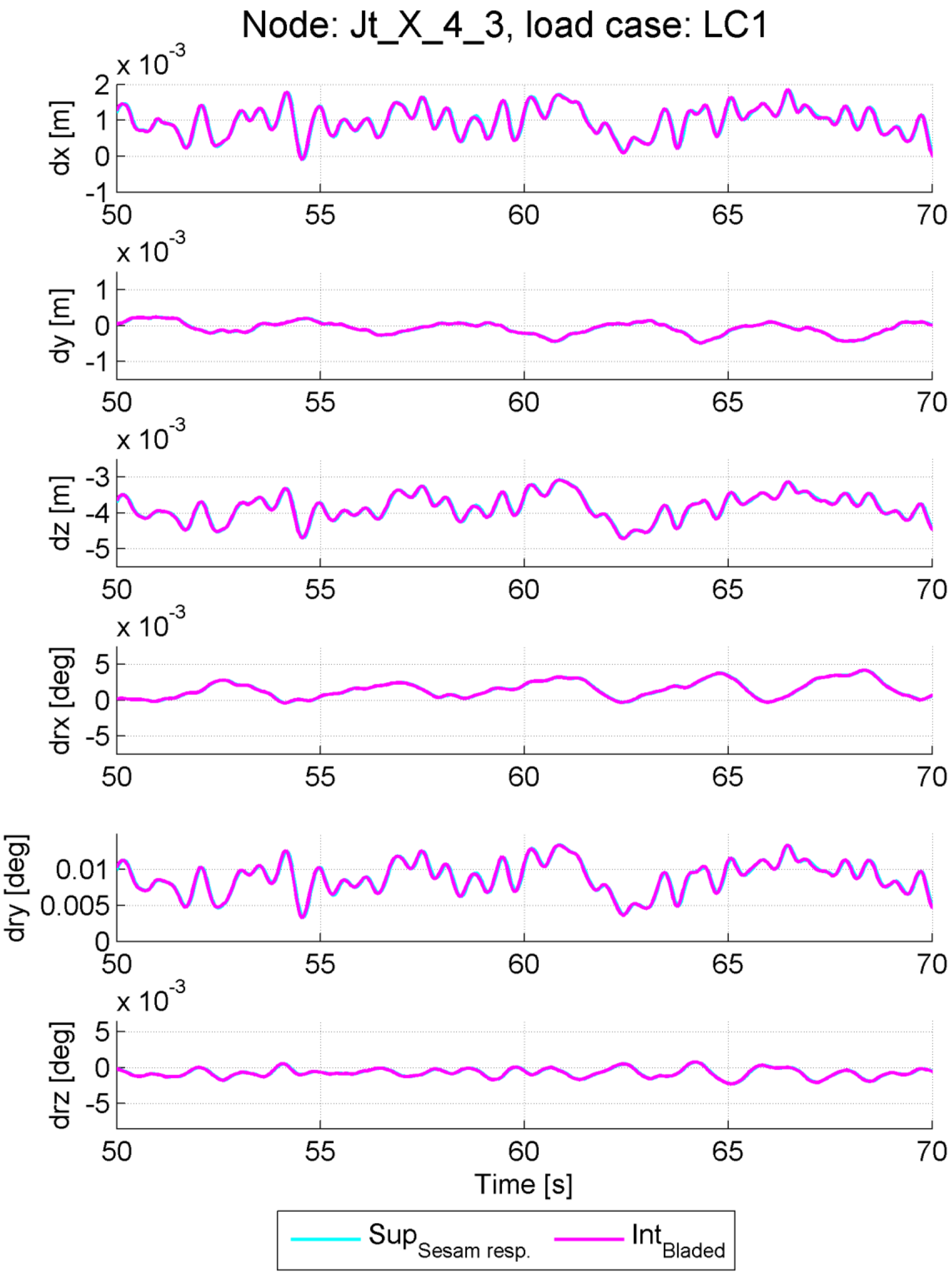


Figure 8-19 Displacement and rotation at joint Jt_X_4_3 over the first 20 seconds time period for model with wind turbine.

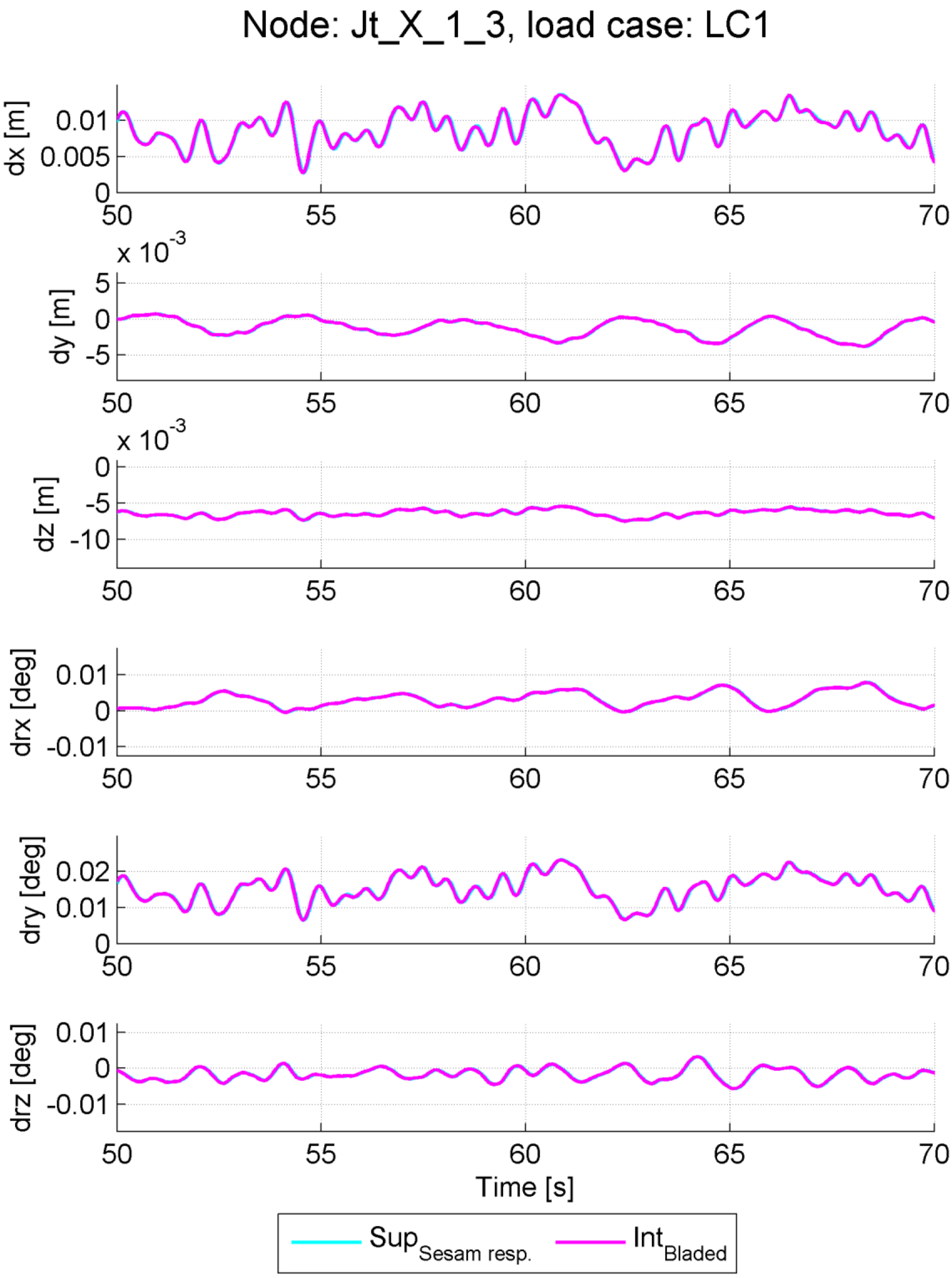


Figure 8-20 Displacement and rotation at joint Jt_X_1_3 over the first 20 seconds time period for model with wind turbine.

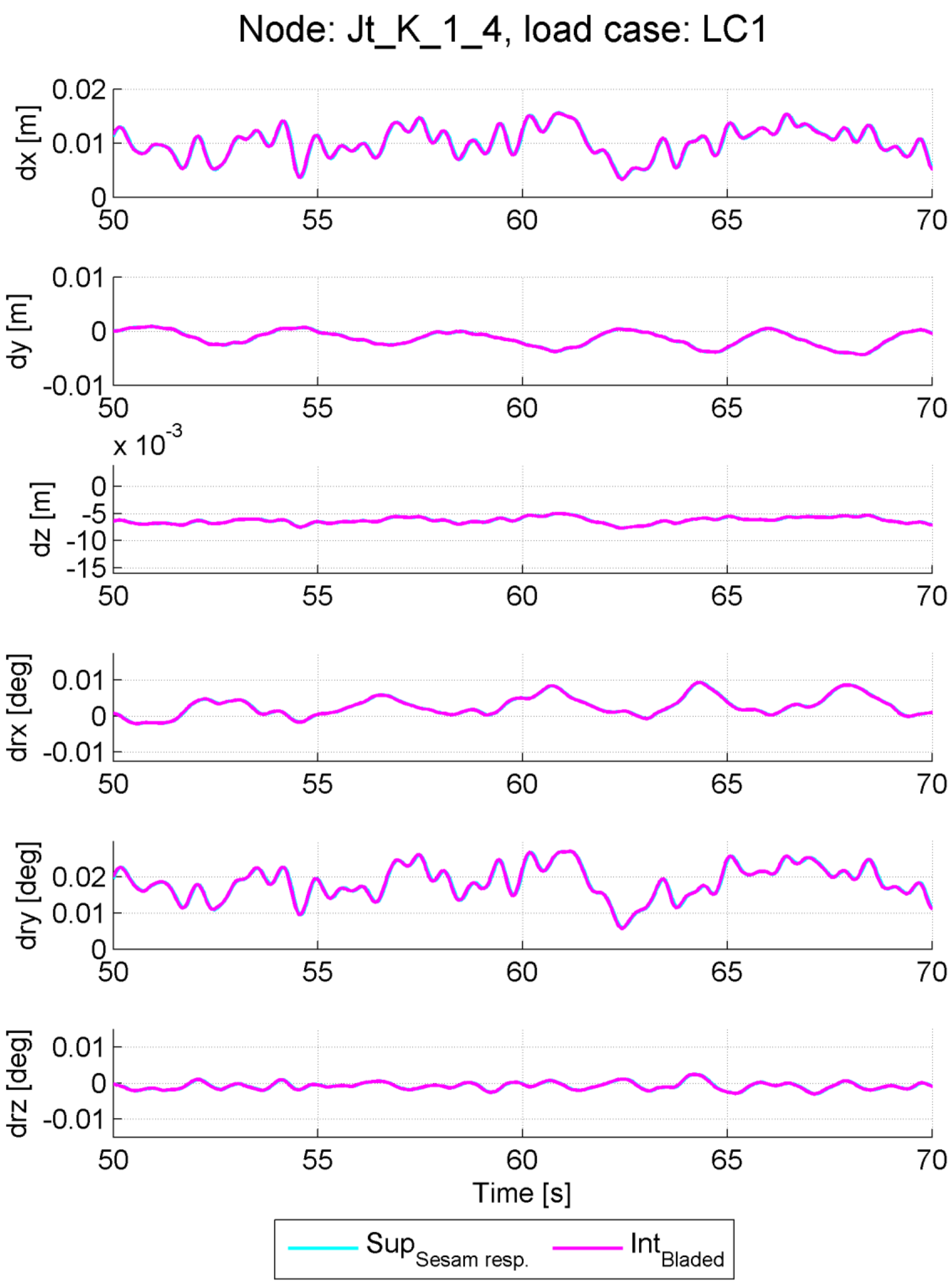


Figure 8-21 Displacement and rotation at joint Jt_K_1_4 over the first 20 seconds time period for model with wind turbine.

8.5.3 Jacket X-brace loads

A load comparison is performed for the braces connecting at the X-joint at the top of the structure, i.e. Jt_X_1_3. The forces and moments are compared in the four elements that are connecting at the joint, see Figure 8-22.

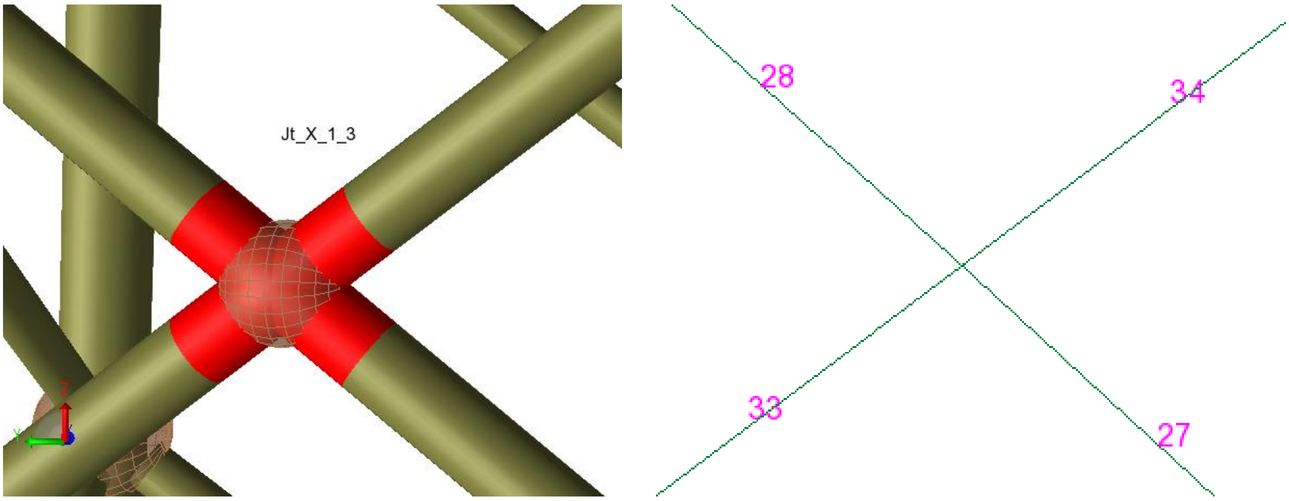


Figure 8-22 Beams (left) and corresponding mesh elements (right) connected to joint Jt_X_1_3.

As can be seen in Figure 8-23 to Figure 8-26, the loads in the superelement model and in the integrated model compare very well and are near-identical.

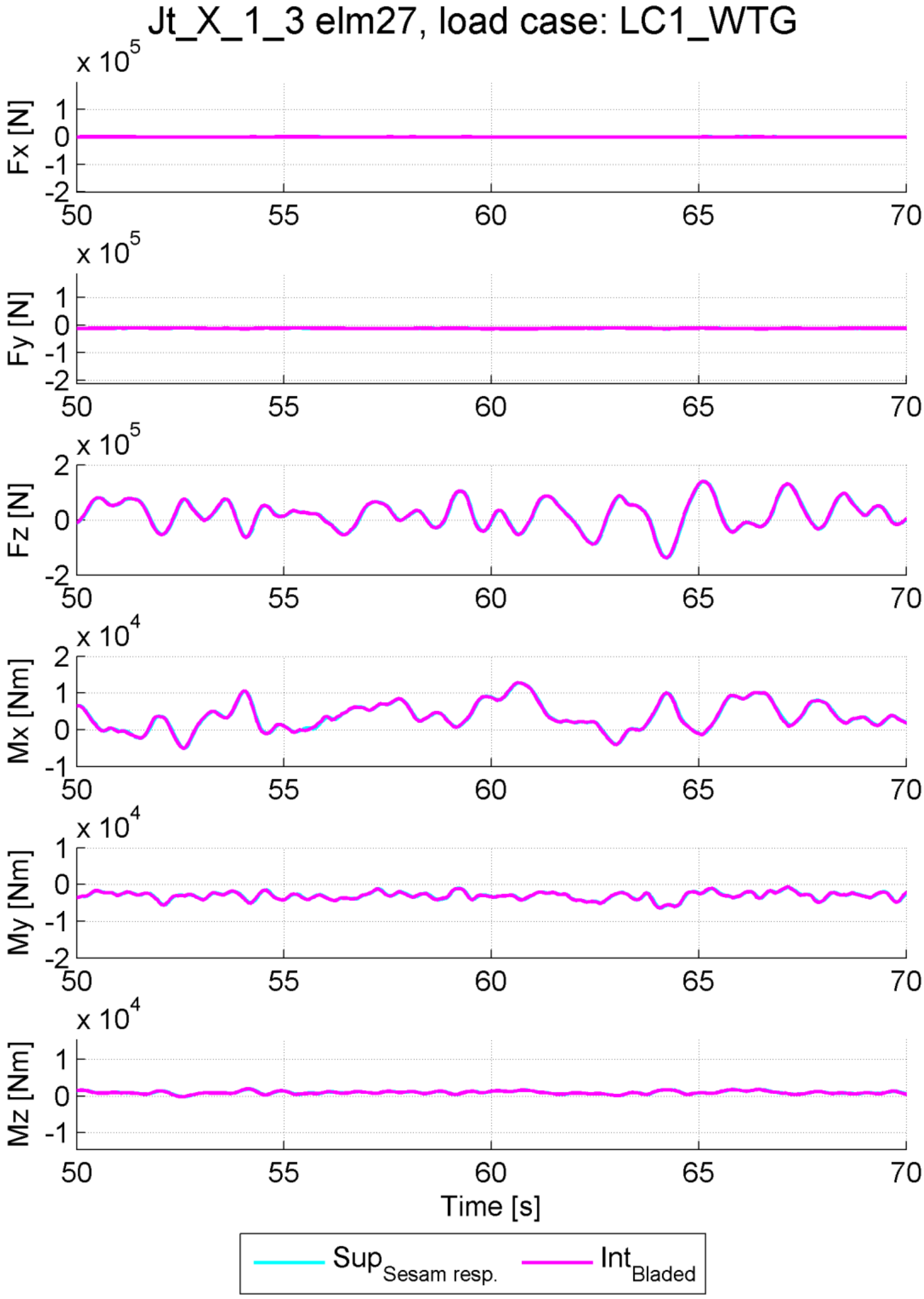


Figure 8-23 X-brace forces and moments at Jt_X_1_3, element 27, over the first 20 seconds time period for model with wind turbine.

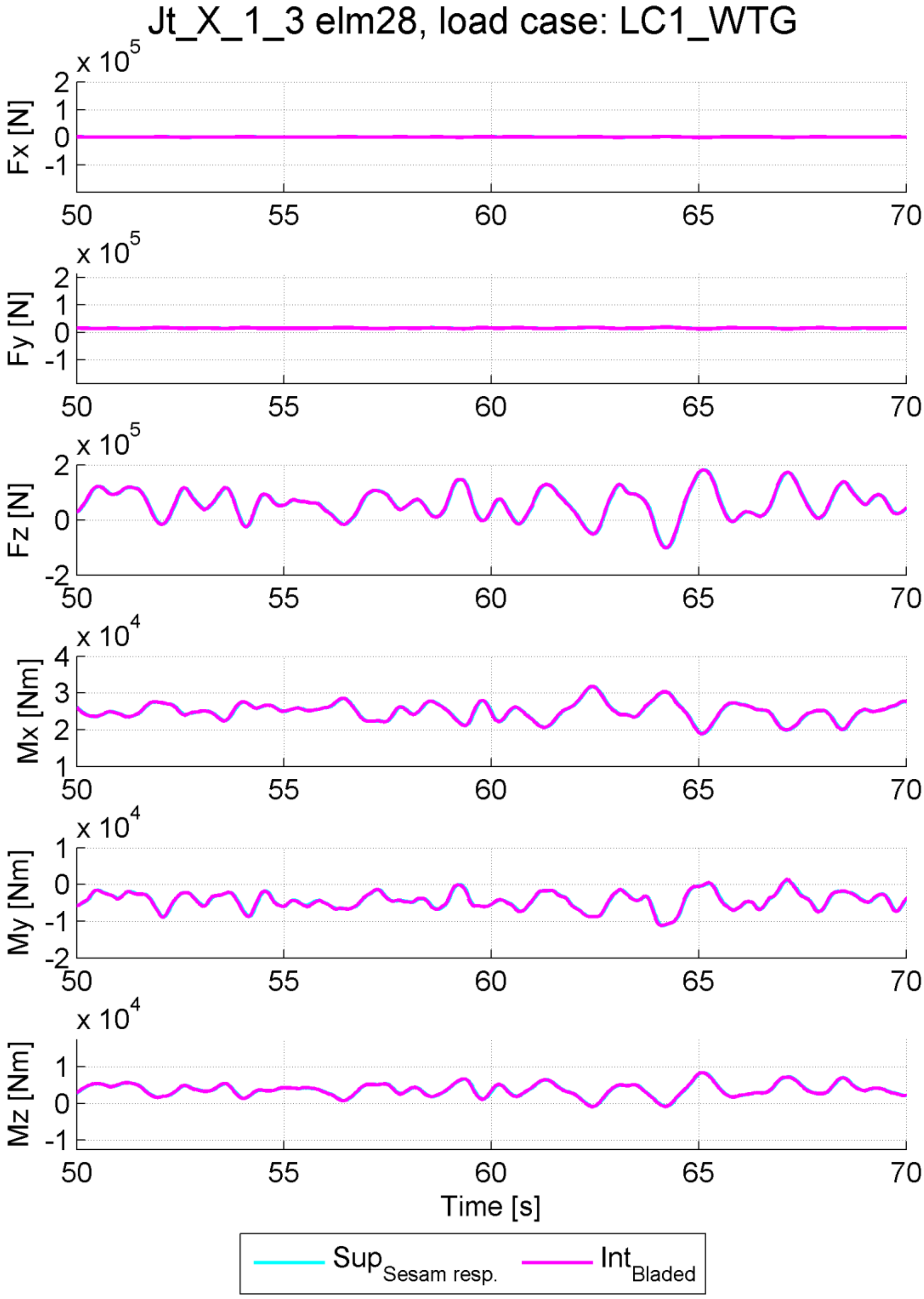


Figure 8-24 X-brace forces and moments at Jt_X_1_3, element 28, over the first 20 seconds time period for model with wind turbine.

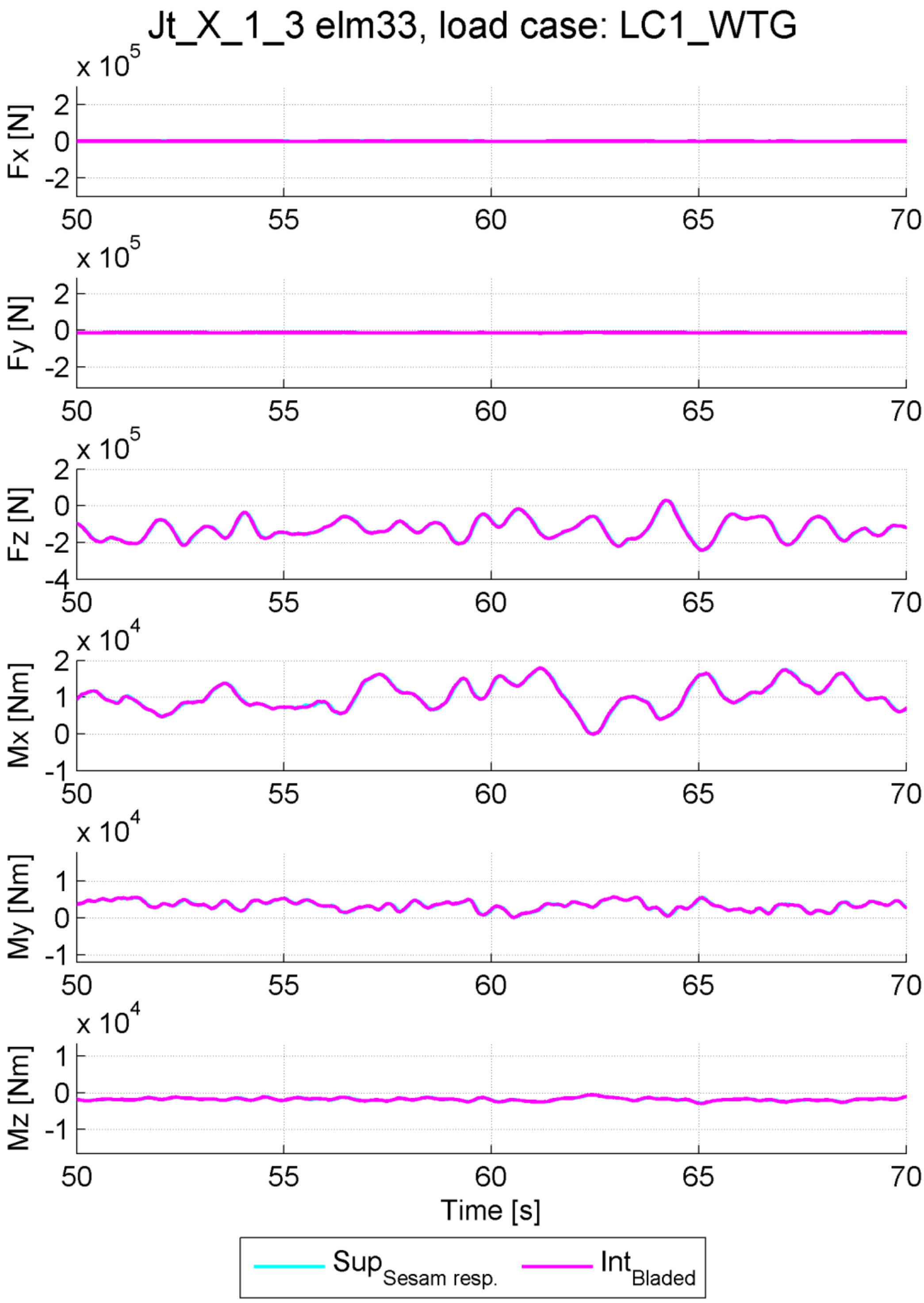


Figure 8-25 X-brace forces and moments at Jt_X_1_3, element 33, over the first 20 seconds time period for model with wind turbine.

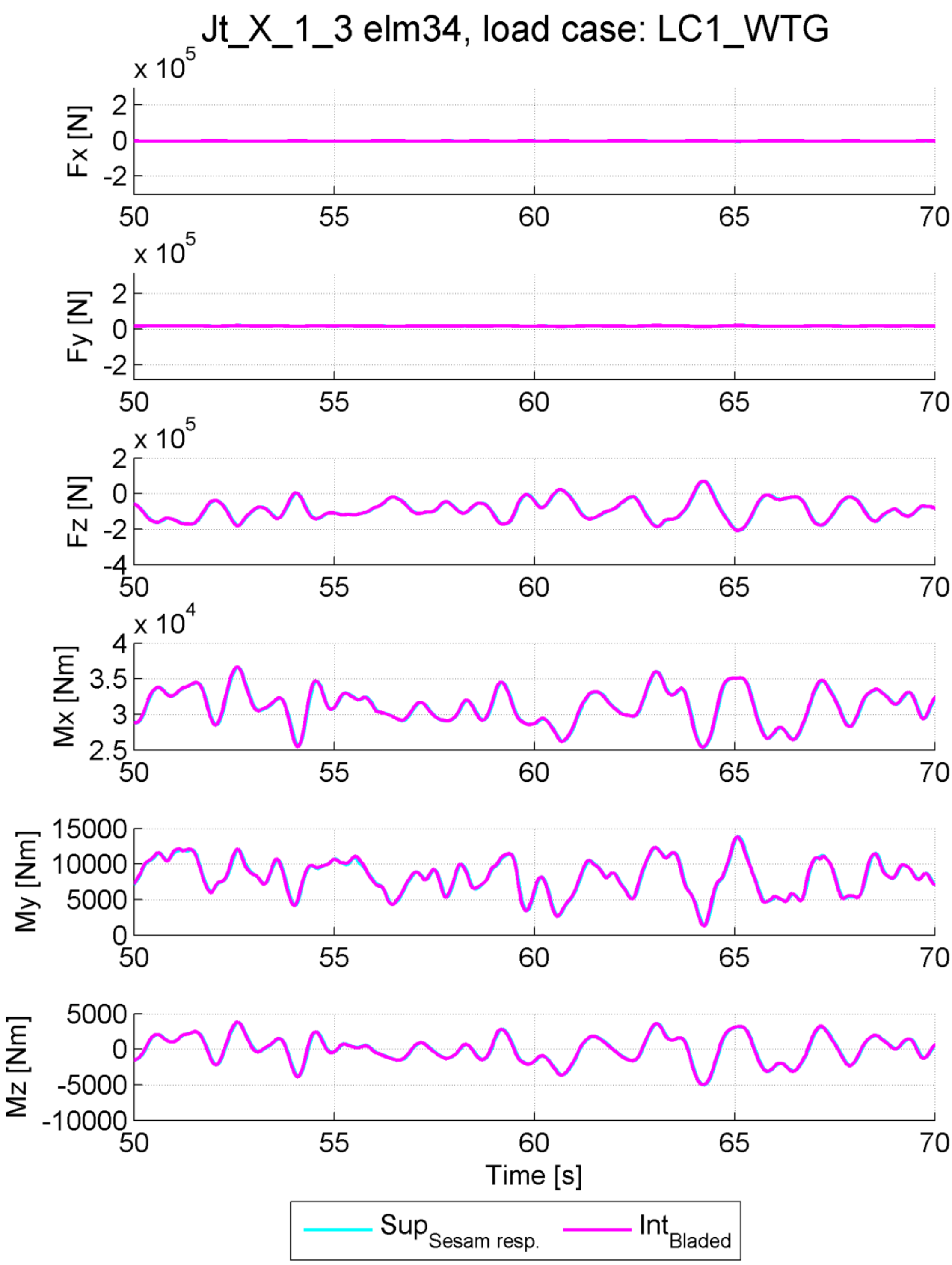


Figure 8-26 X-brace forces and moments at Jt_X_1_3, element 34, over the first 20 seconds time period for model with wind turbine.

8.5.4 Tower top motions due to wave and wind loading

In addition to results at the interface and at the jacket joints, the motions at the tower top are compared. These should give a good indication on how well the different models compare. 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. Results that compare well at the tower top should therefore give a good indication on how closely the system has been modelled in the different ways.

The tower top displacements are shown in Figure 8-27. The Bladed integrated model includes the wind turbine and jacket in a single model, whereas the superelement model is a combination of the Sesam superelement combined with the wind turbine in Bladed. The displacements compare well, and no significant differences are seen.

For the tower top velocities, shown in Figure 8-28, the results are similar as for the displacements, i.e. good agreement is seen between the different systems. Also the tower top accelerations displayed in Figure 8-29 show very similar behaviour.

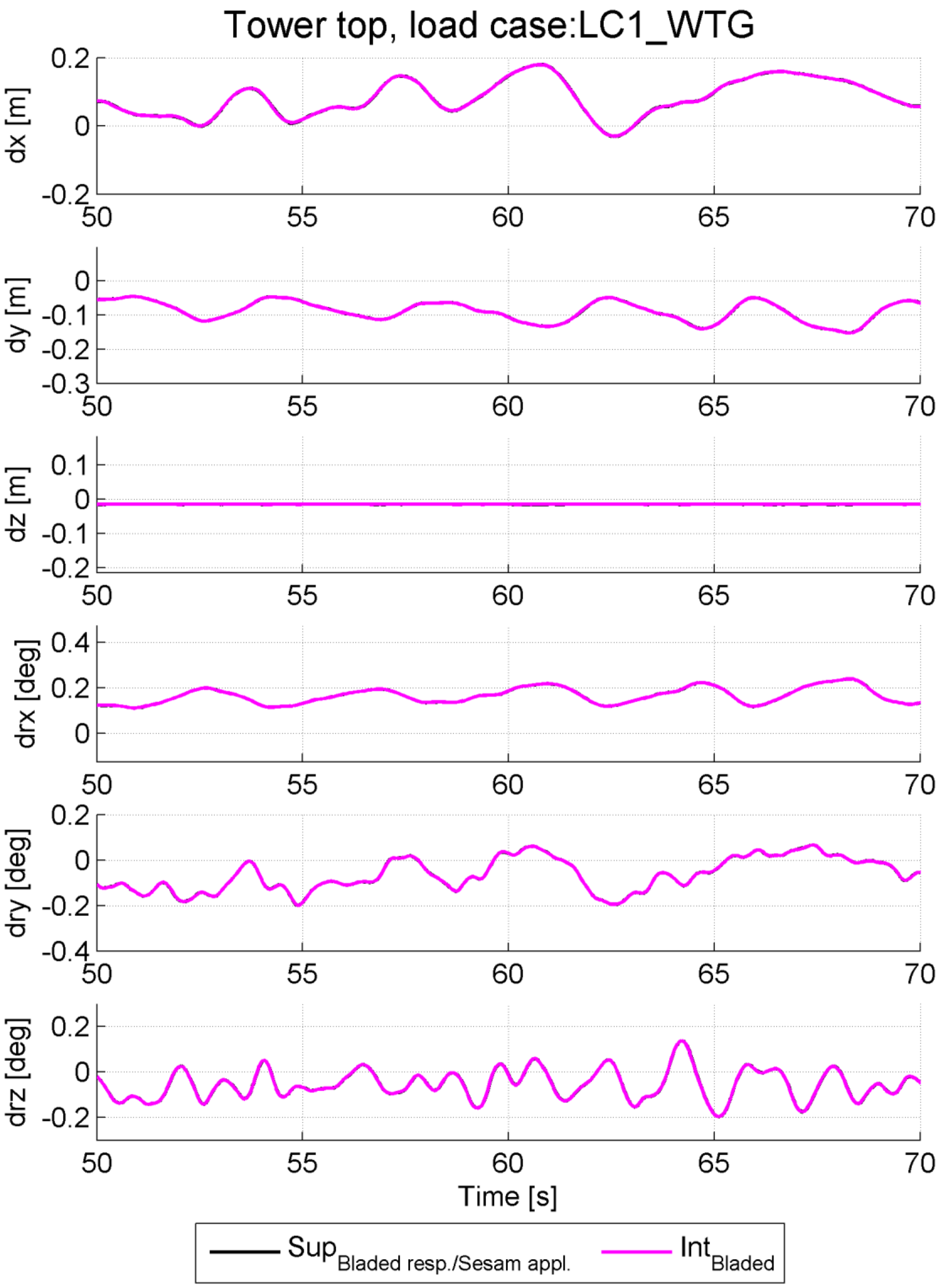


Figure 8-27 Displacements at the tower top over the first 20 seconds time period for model with wind turbine.

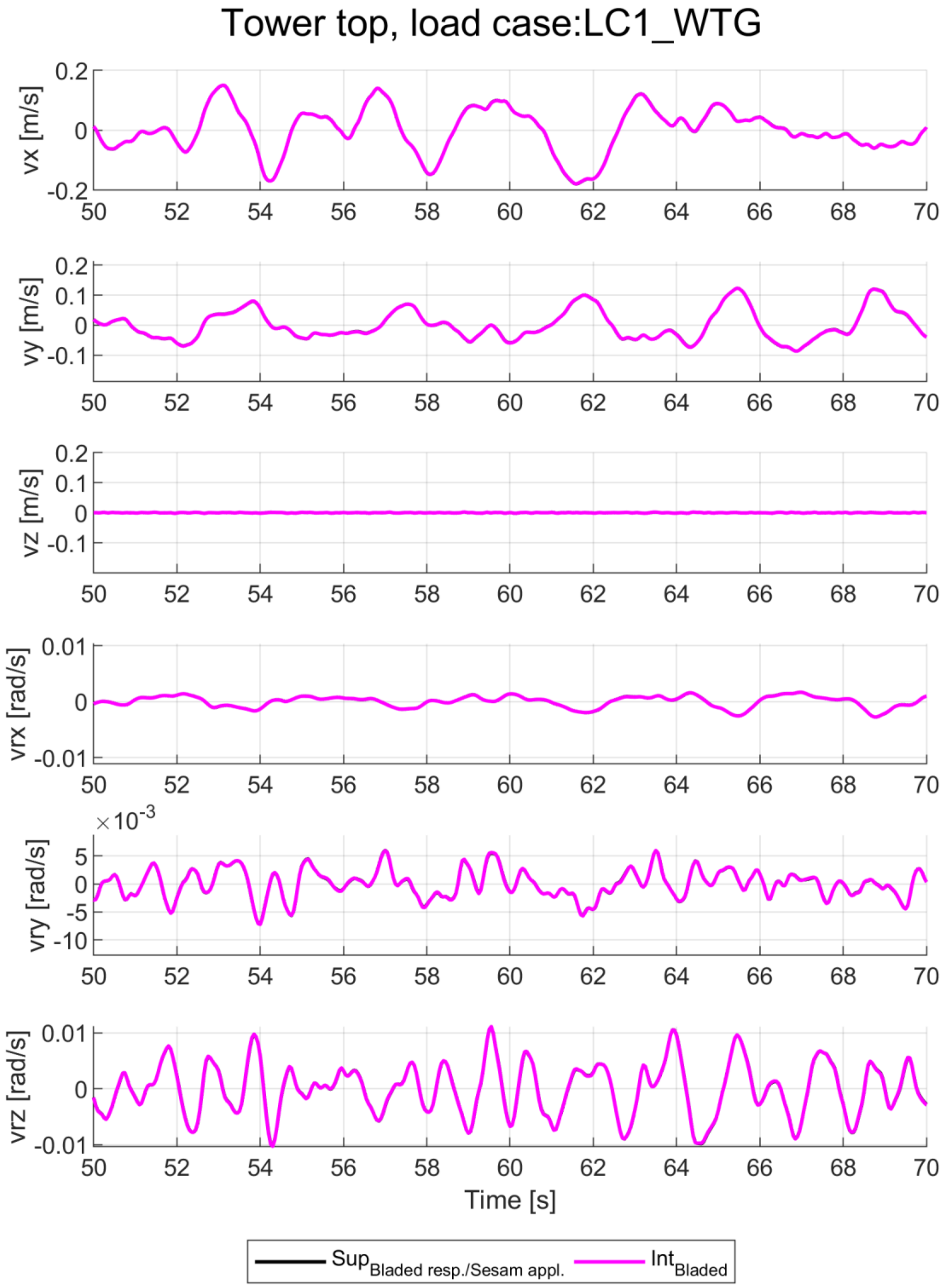


Figure 8-28 Velocities at the tower top over the first 20 seconds time period for model with wind turbine.

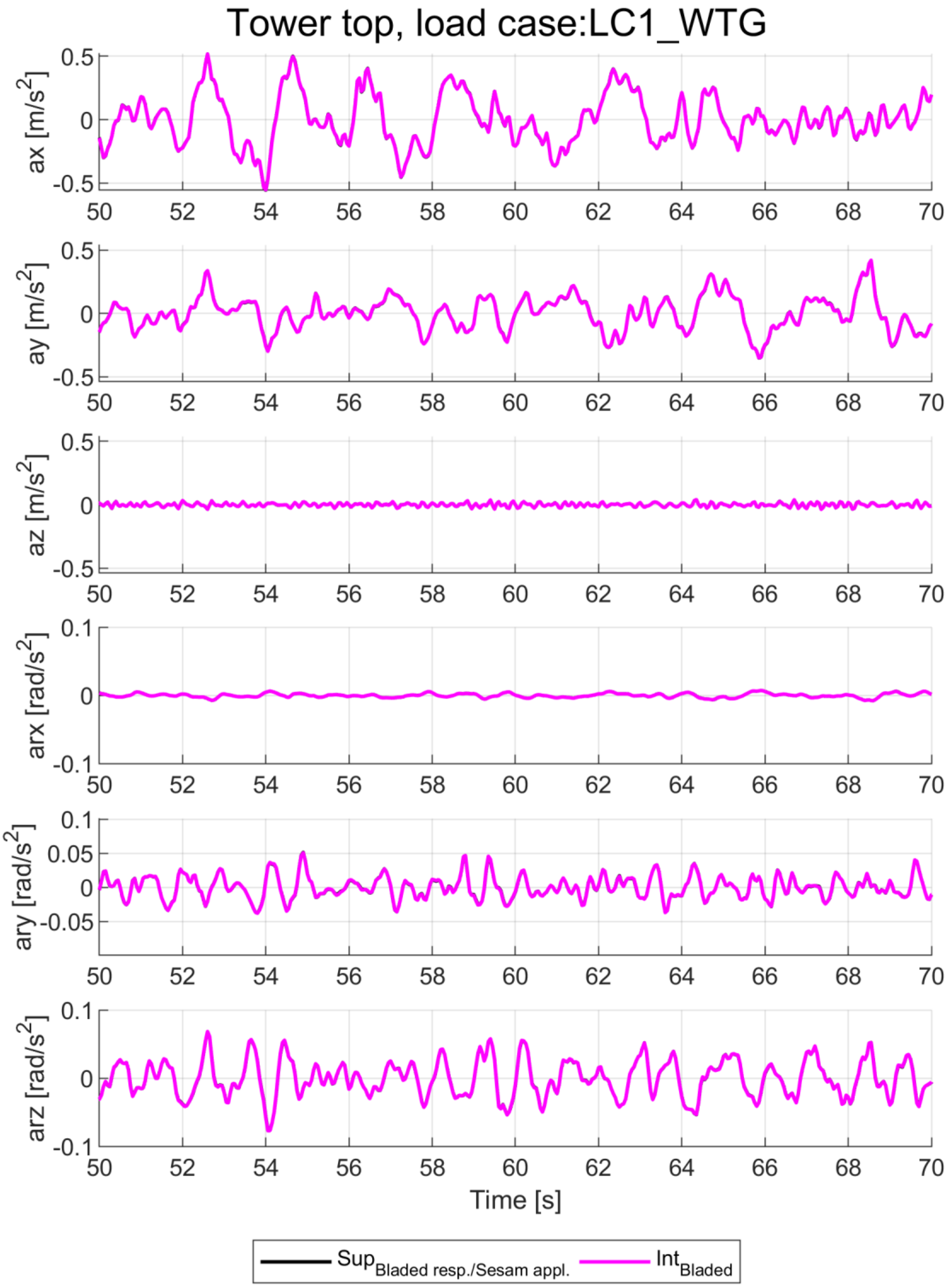


Figure 8-29 Accelerations at the tower top over the first 20 seconds time period for model with wind turbine.

8.6 Result comparison for model with wind turbine under extreme conditions of combined wave and wind loading

This section contains a similar comparison as section 8.5, but with the notable difference that in this section the wave and wind loading are extreme conditions. The load case description is defined in Table 3-3. The same models and damping parameters are used in as section 8.5.

The original extreme case in this section is a constrained wave. The constrained wave including the irregular background wave time history is generated in Sesam. The wave needs to be regenerated in Bladed for the integrated run in order to perform a proper comparison. The wave components in the Sesam-generated constrained wave surface elevation are extracted, so that the wave can be reproduced in Bladed by superimposing linear Airy waves. It should be noted that this means that also the constrained part of the surface elevation, which in Sesam is modelled using NewWave and Stream function theory, is then modelled with Airy wave theory in the integrated case in Bladed. This needs to be taken into account in the comparison. Alternatively, the constrained wave could have been modelled using Bladed’s built-in constrained wave generator, also allowing the use of NewWave and Stream function theory, but in that case the irregular background wave history would not match between Sesam and Bladed due to different random sea generators being used. Reproducing the full wave history using Airy waves for the integrated run in Bladed is the chosen way forward for the constrained wave case.

Since the constrained wave comparison is not based on identical wave theories, simulations are run with two other waves in addition, being an irregular wave and a regular wave. These allow a closer comparison between Sesam and Bladed for both wave types under extreme conditions, since the exact same waves can be used in both programs.

Results in this section are displayed for the region around 200 s, which is the time of occurrence of the constrained wave (the same time range is displayed for the irregular and regular wave cases too).

8.6.1 Sea surface elevations

For the extreme conditions, different sea surface elevations result from the simulations. The sea surface elevations are identical in Sesam and Bladed (with the sidenote that the constrained wave for the integrated run in Bladed is reproduced using Airy waves only as explained above). The surface elevations are as shown in Figure 8-30.

From the plots, it can be seen that the irregular case matches the background irregular wave history of the constrained case. It can also be seen that the regular case matches the occurrence of the constrained wave peak and troughs around 200 s of the constrained case. The irregular and regular cases are generated using the same wave theories in Sesam and Bladed and should therefore be able to give a more correct comparison between Sesam and Bladed than what is possible for the constrained wave.

8.6.2 Interface loads and motion due to wave and wind loading

The resulting loads, displacements, velocities and accelerations at the interface are shown in sections 8.6.2.1, 8.6.2.2 and 8.6.2.3 for the constrained wave, irregular wave and regular wave respectively.

For all plots, it can be seen that the results in Sesam and Bladed are near-identical. There is one exception, which is that of the displacement in the wave direction (dx) and the rotation caused by this (dry) (and, in some degree, the velocities) at the interface for the constrained wave case, see Figure 8-32. Some difference can be seen between the integrated and superelement cases, especially in the regions 186-191 s, around 200 s, and 210-215 s. These time intervals correspond to the peaks of the constrained wave. The difference can be explained by the difference in wave theories used for the constrained wave part of the wave simulation in the integrated run in Bladed versus that in the superelement run generated by Sesam, due to the reproduction of the Sesam wave in Bladed using Airy wave components. From the corresponding plots for the irregular and regular wave cases, for which the same wave theories are used in Sesam and Bladed, the results can be seen to be identical, confirming that the wave theory is the cause of the differences.

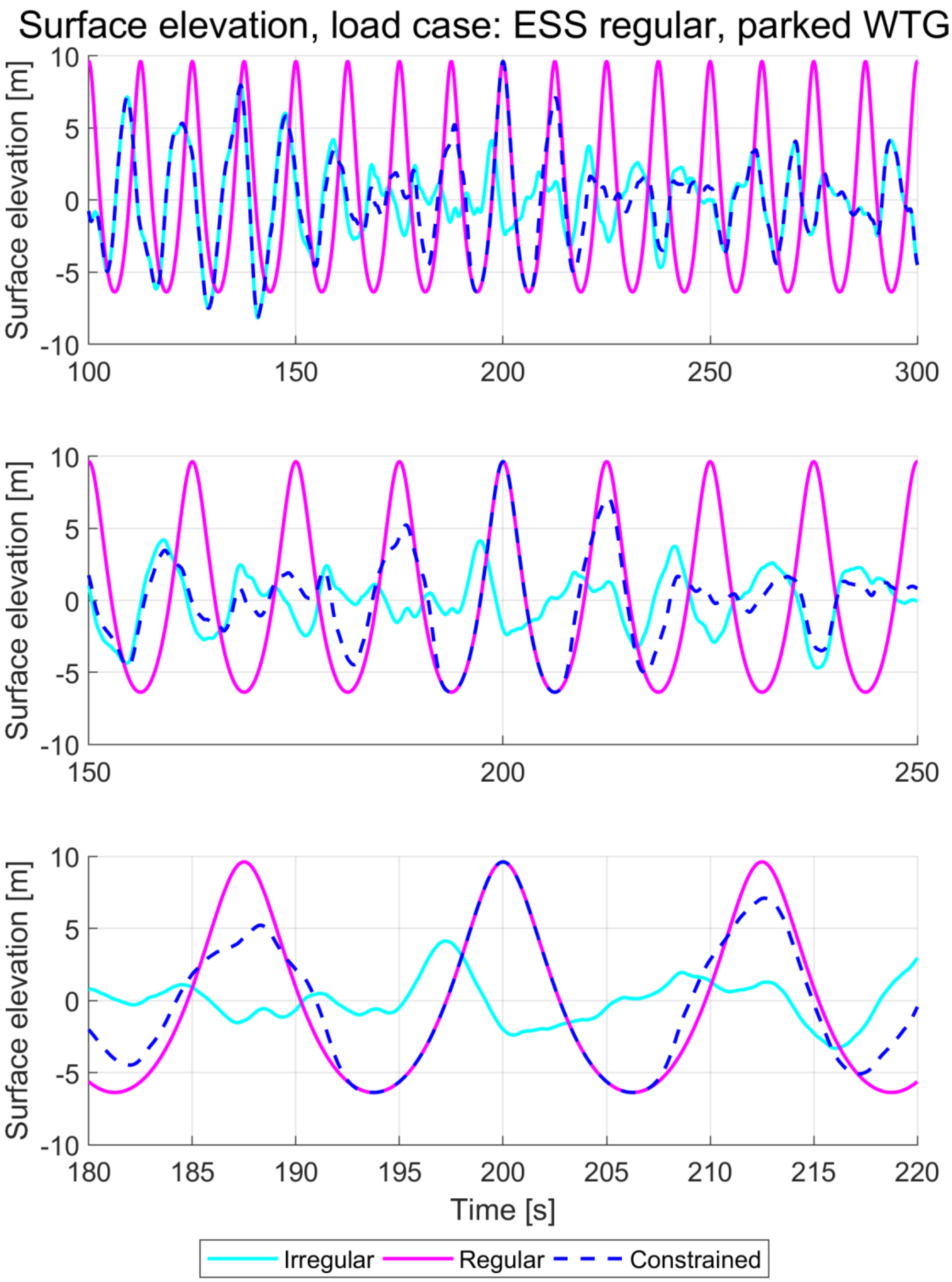


Figure 8-30 Sea surface elevations for the extreme load cases

8.6.2.1 Constrained wave

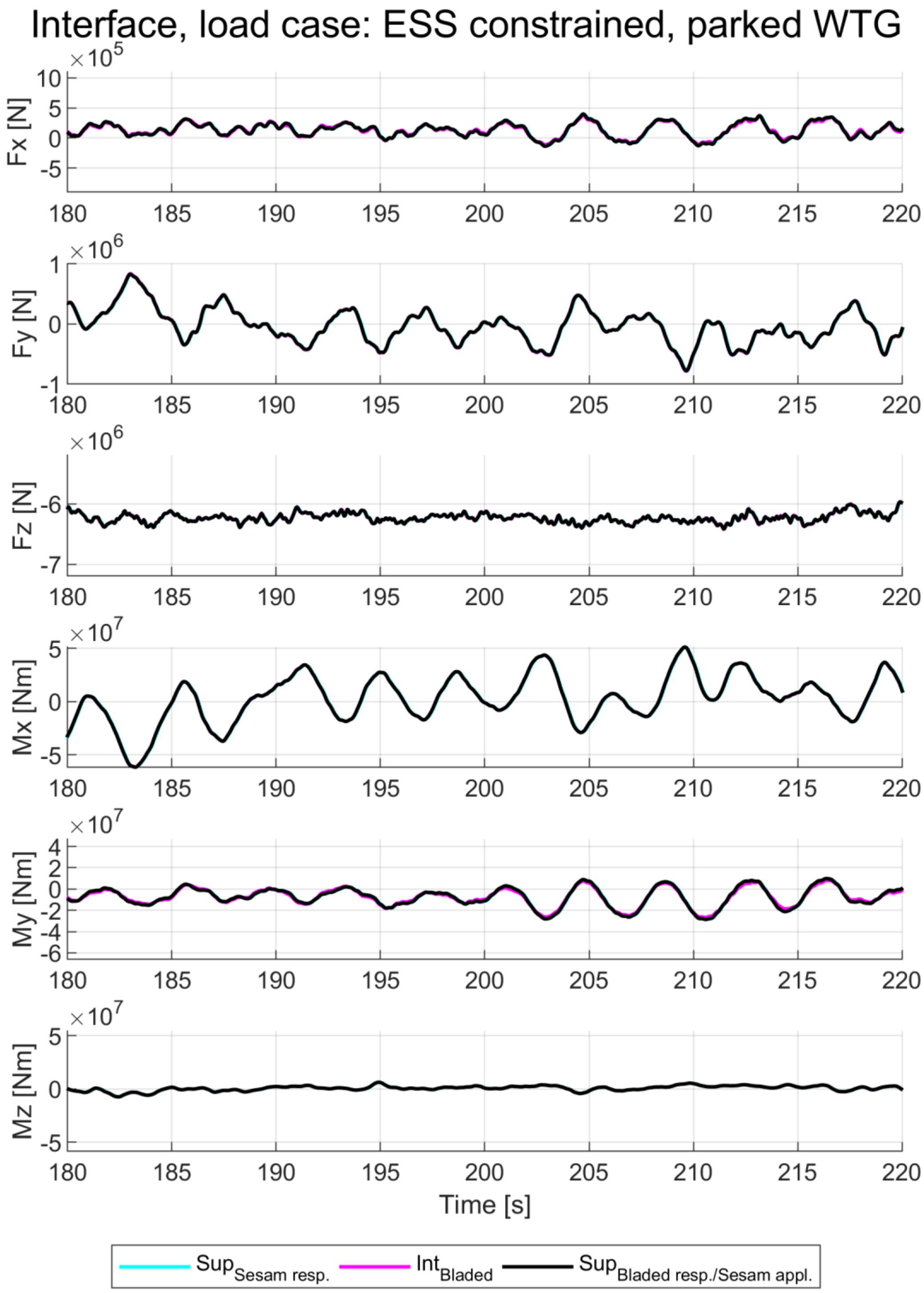


Figure 8-31 Loads at the interface around 200 s for the extreme load case with constrained wave.

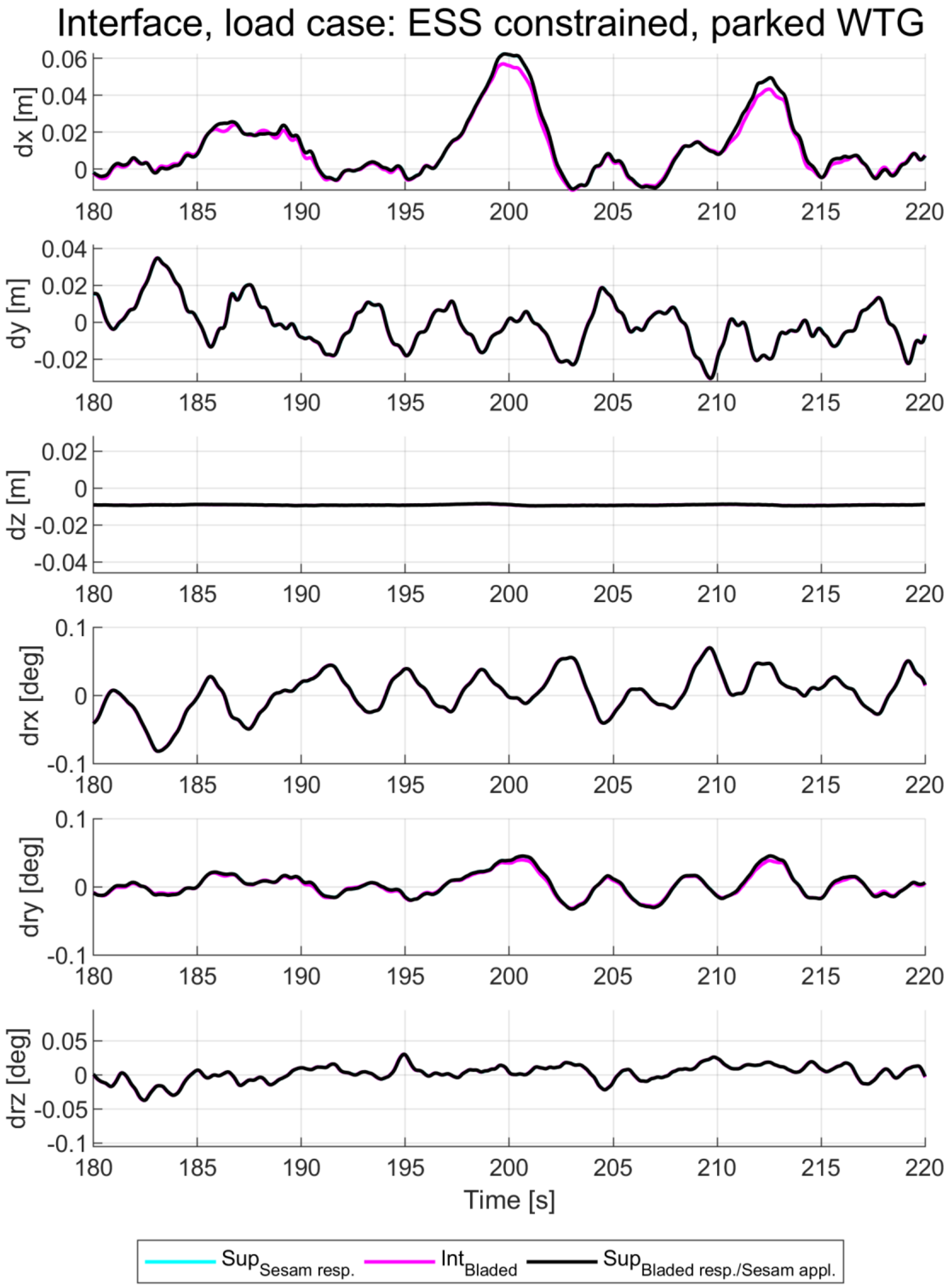


Figure 8-32 Displacements at the interface around 200 s for the extreme load case with constrained wave.

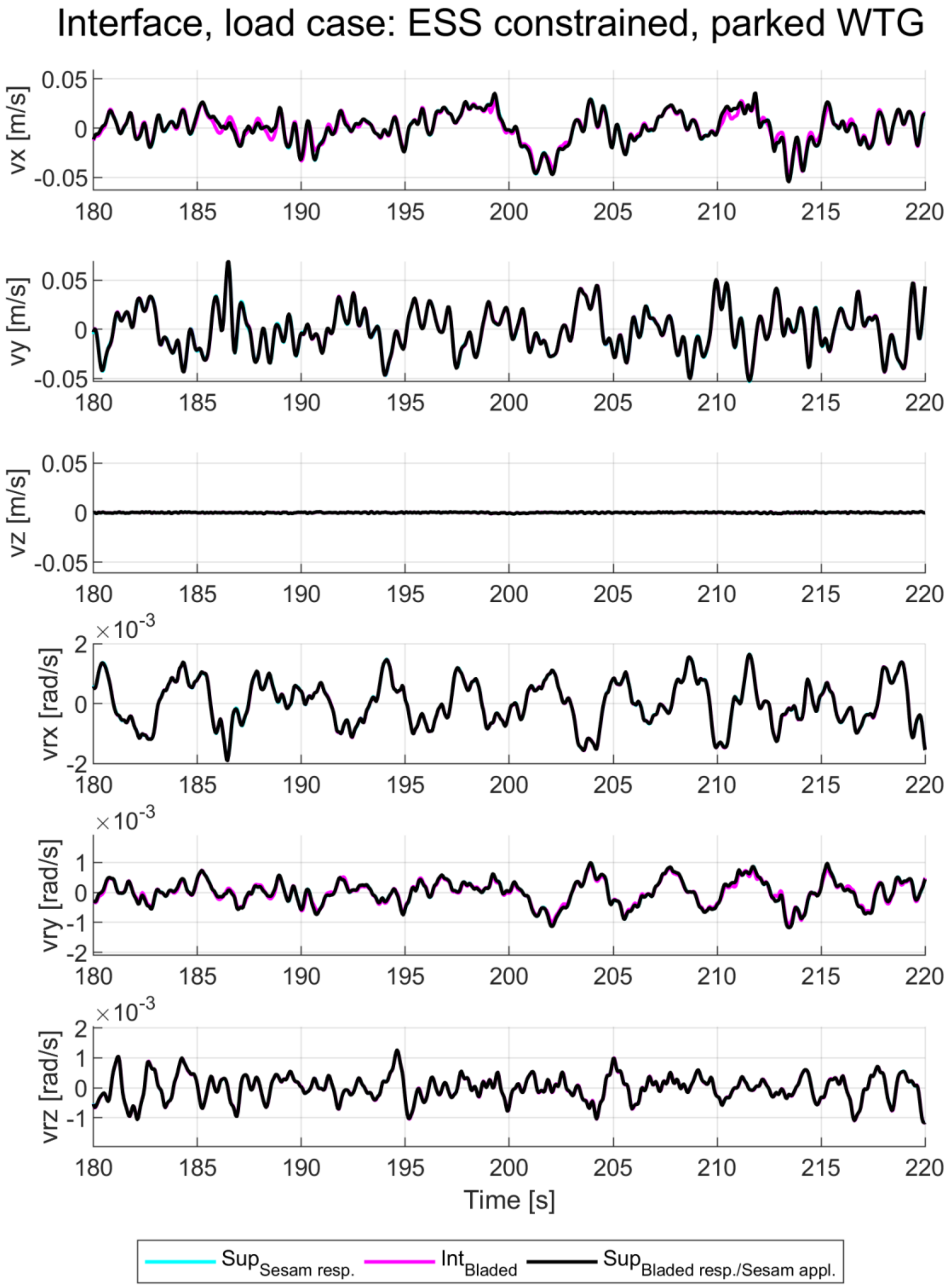


Figure 8-33 Velocities at the interface around 200 s for the extreme load case with constrained wave.

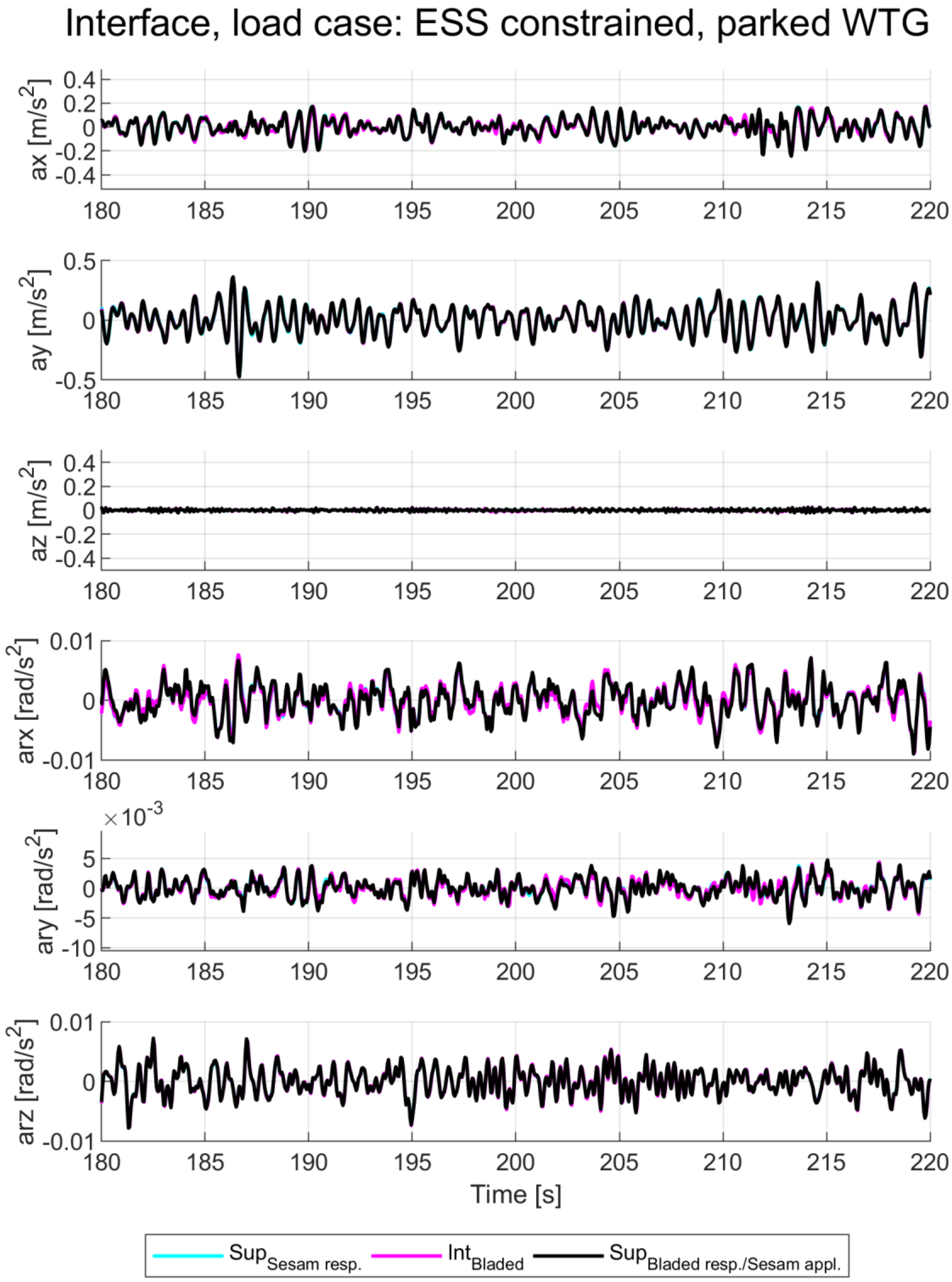


Figure 8-34 Accelerations at the interface around 200 s for the extreme load case with constrained wave.

8.6.2.2 Irregular wave

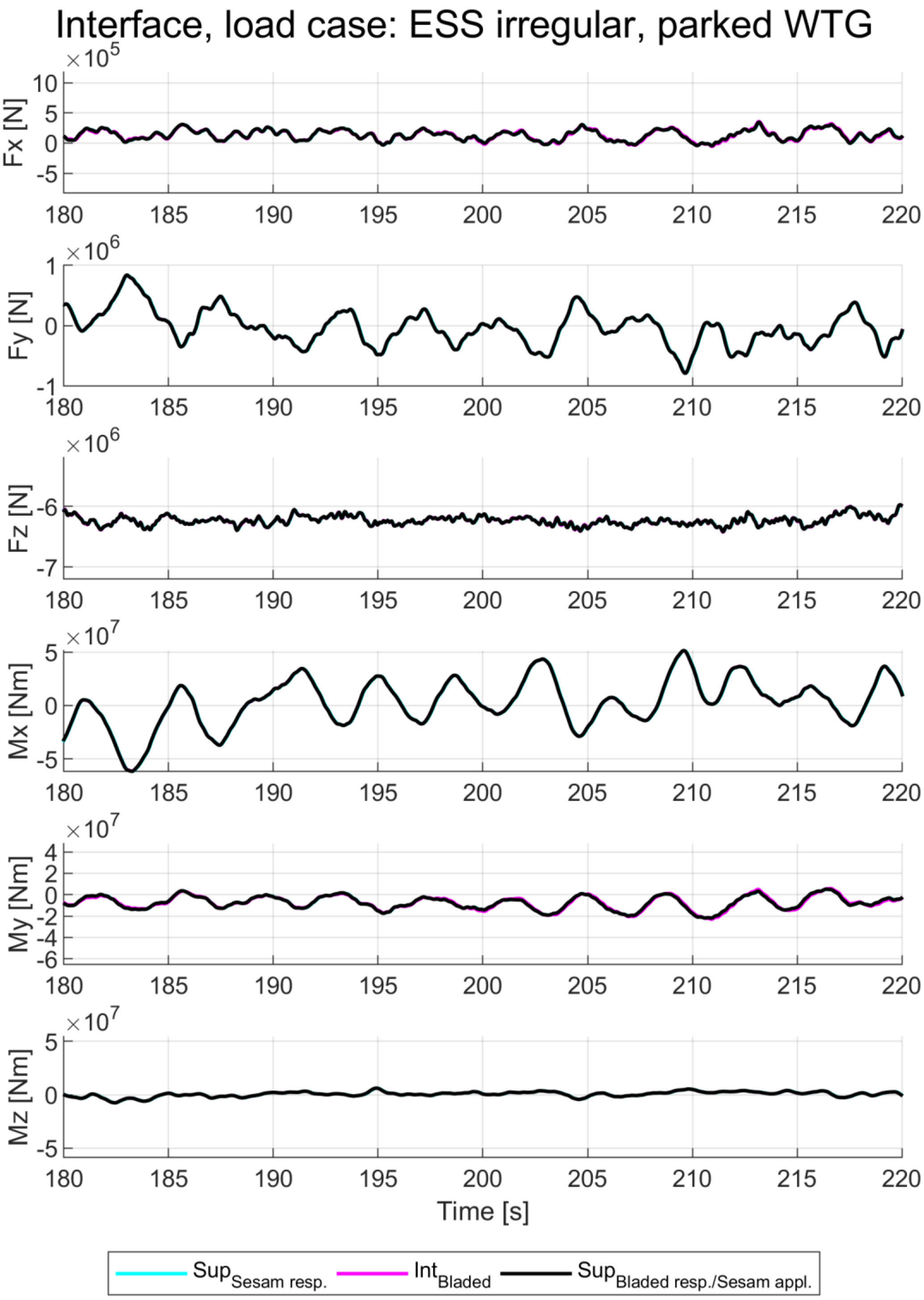


Figure 8-35 Loads at the interface around 200 s for the extreme load case with irregular wave.

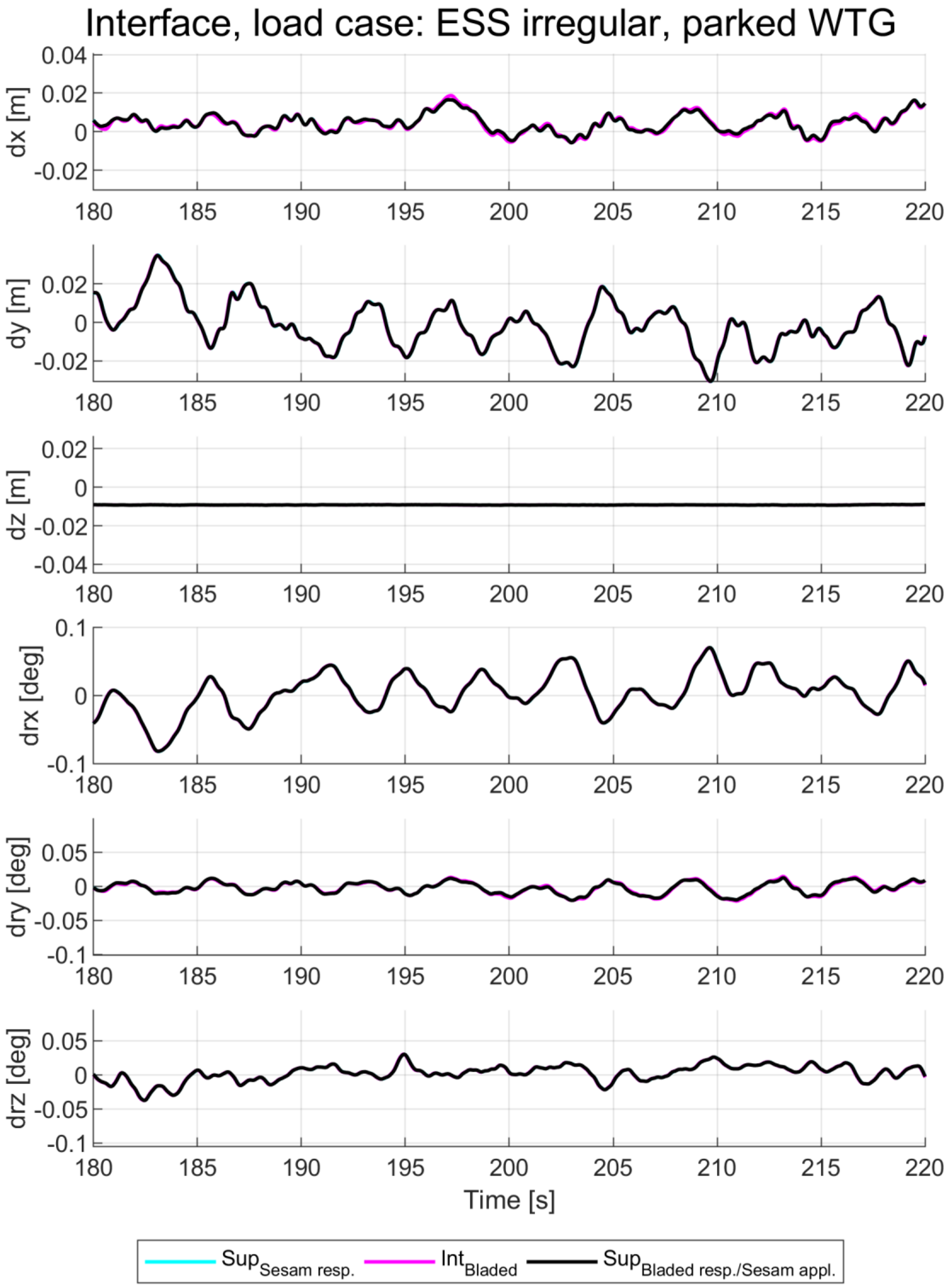


Figure 8-36 Displacements at the interface around 200 s for the extreme load case with irregular wave.

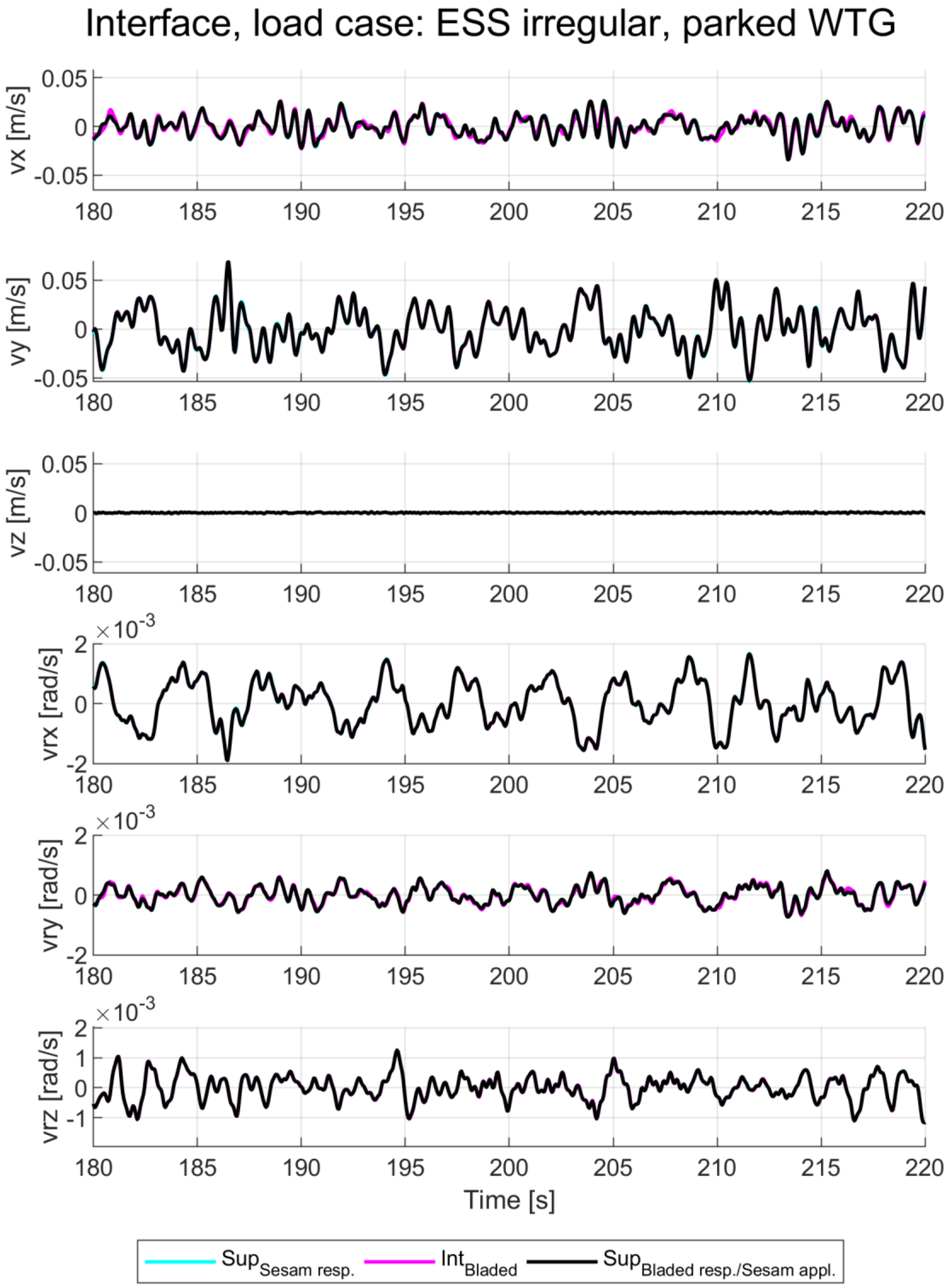


Figure 8-37 Velocities at the interface around 200 s for the extreme load case with irregular wave.

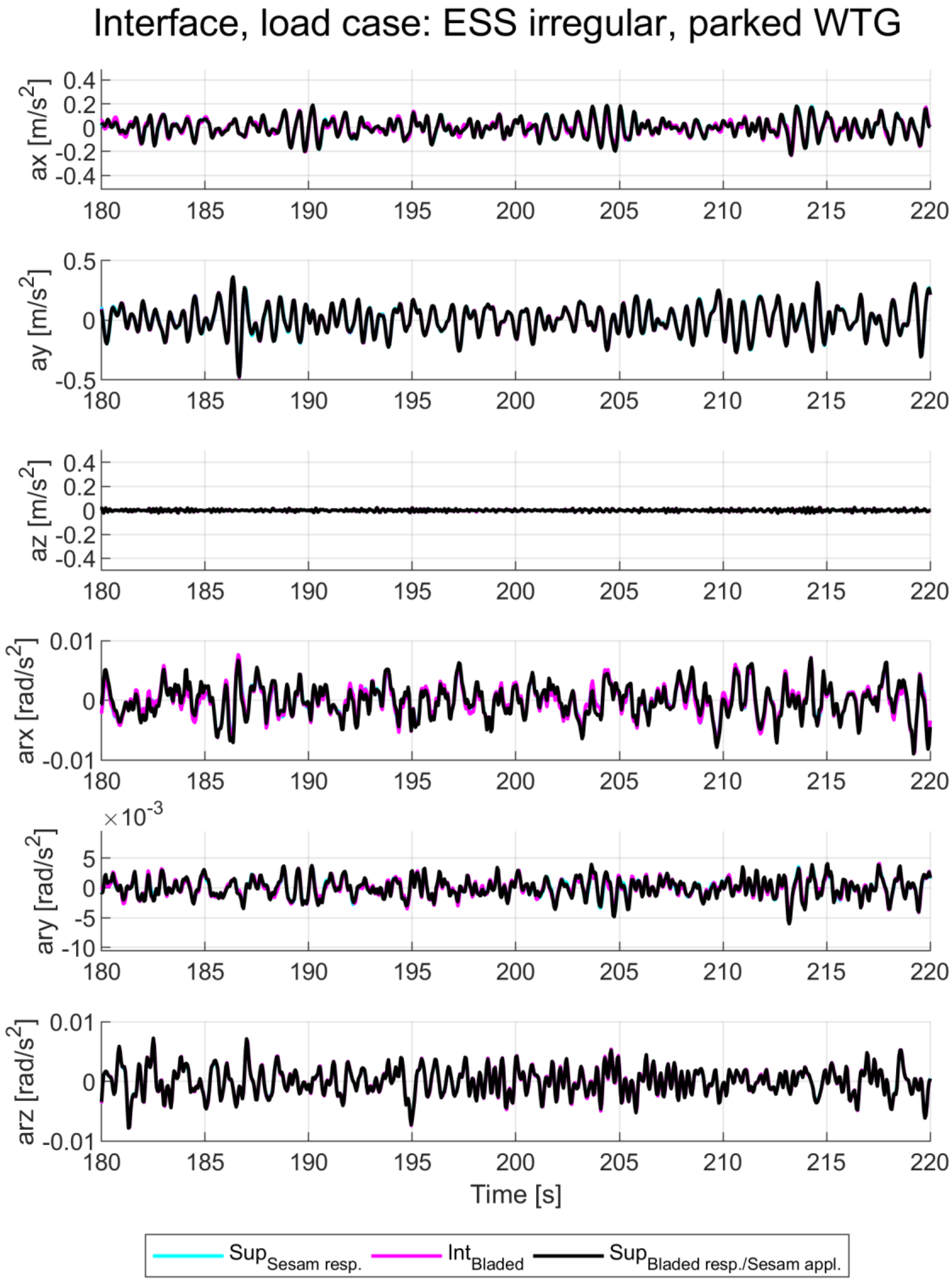


Figure 8-38 Accelerations at the interface around 200 s for the extreme load case with irregular wave.

8.6.2.3 Regular wave

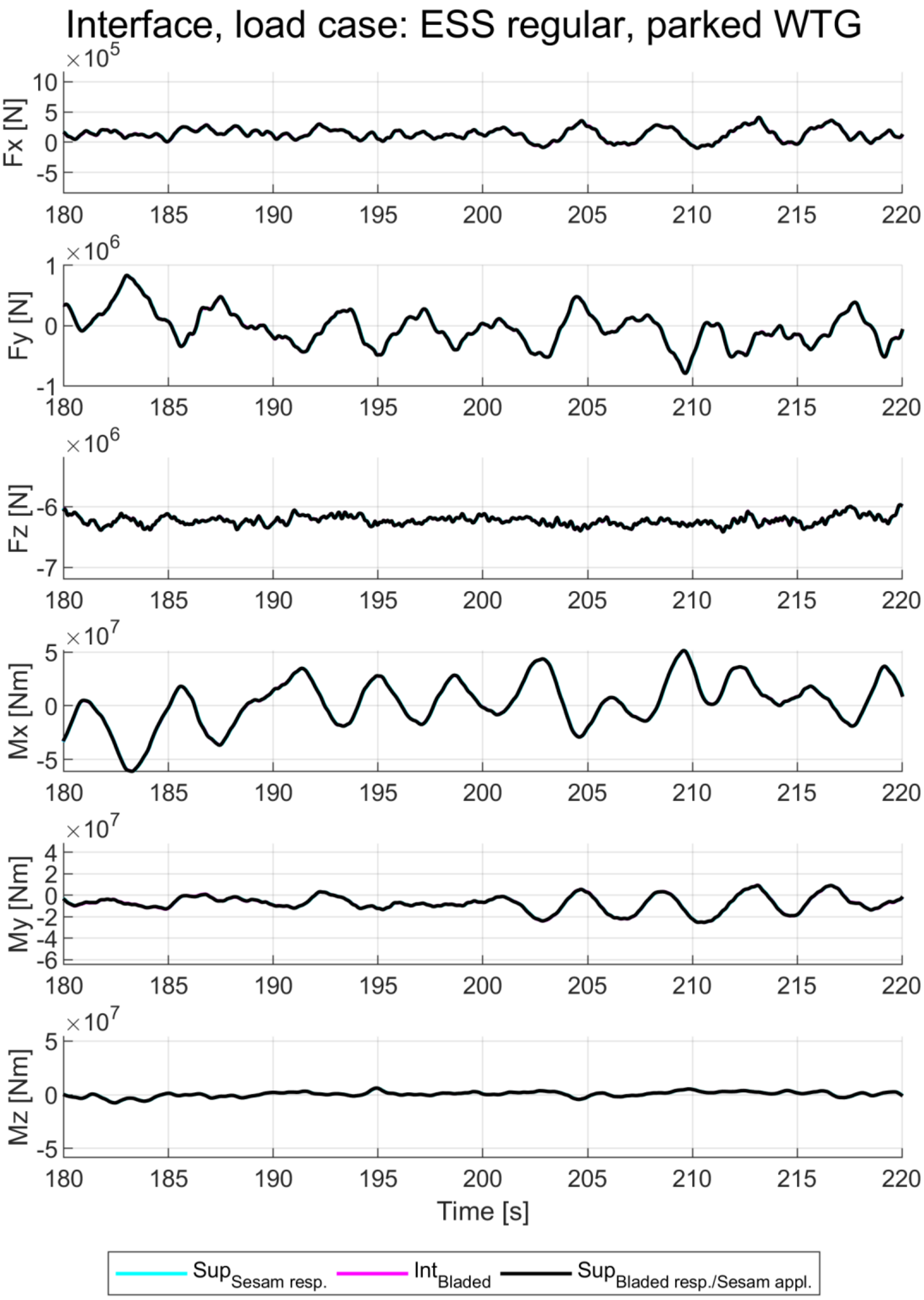


Figure 8-39 Loads at the interface around 200 s for the extreme load case with regular wave.

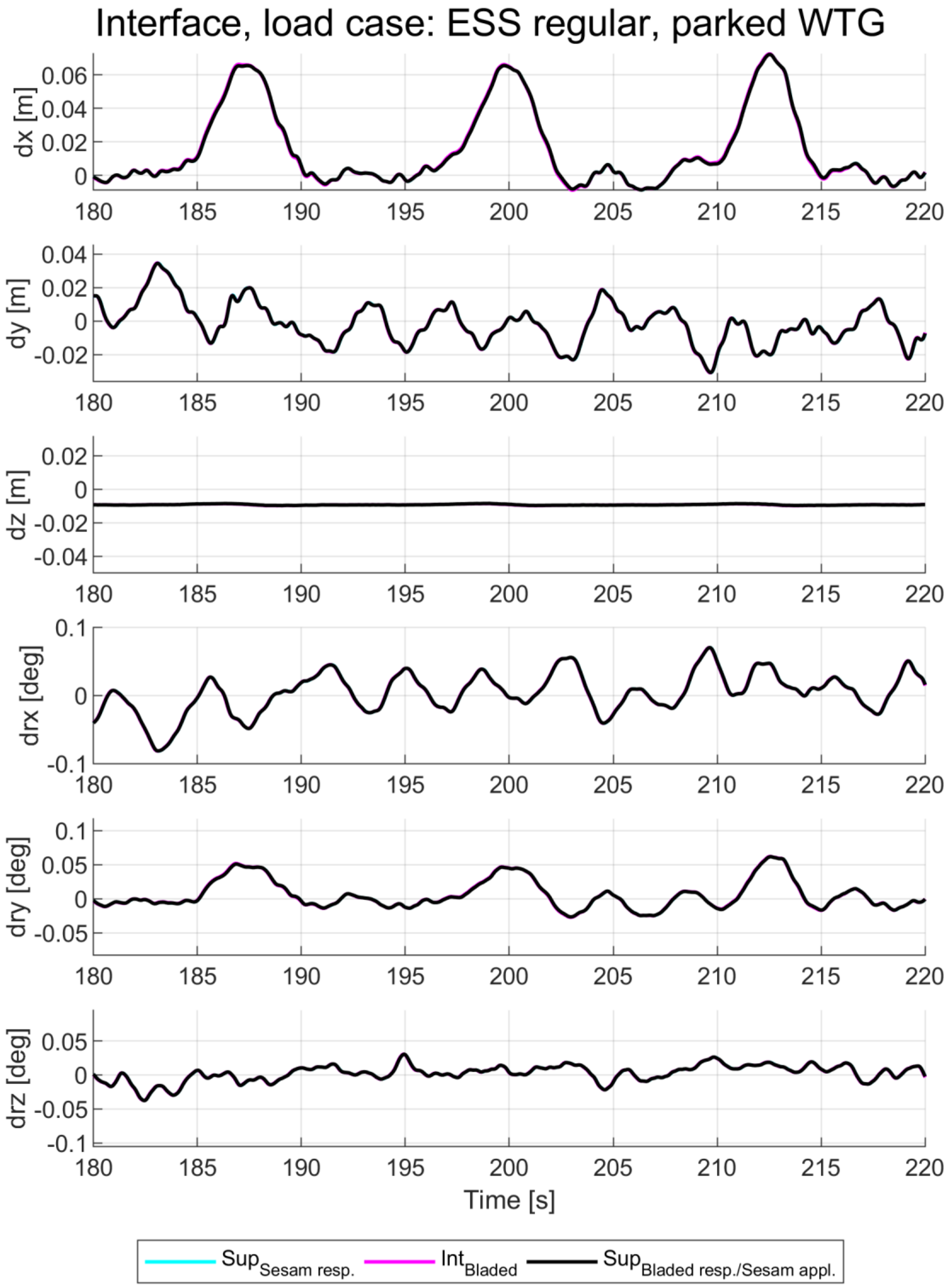


Figure 8-40 Displacements at the interface around 200 s for the extreme load case with regular wave.

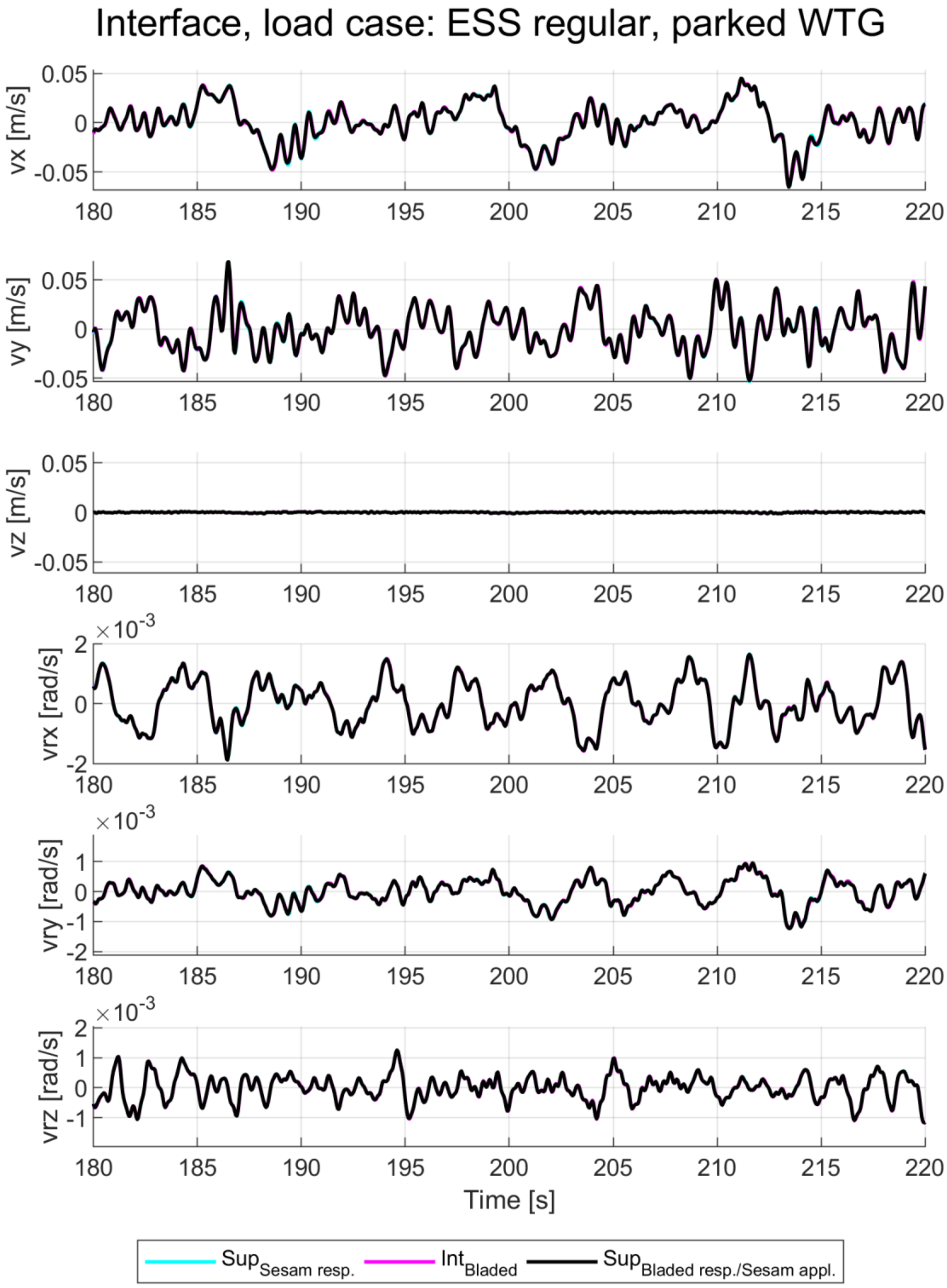


Figure 8-41 Velocities at the interface around 200 s for the extreme load case with regular wave.

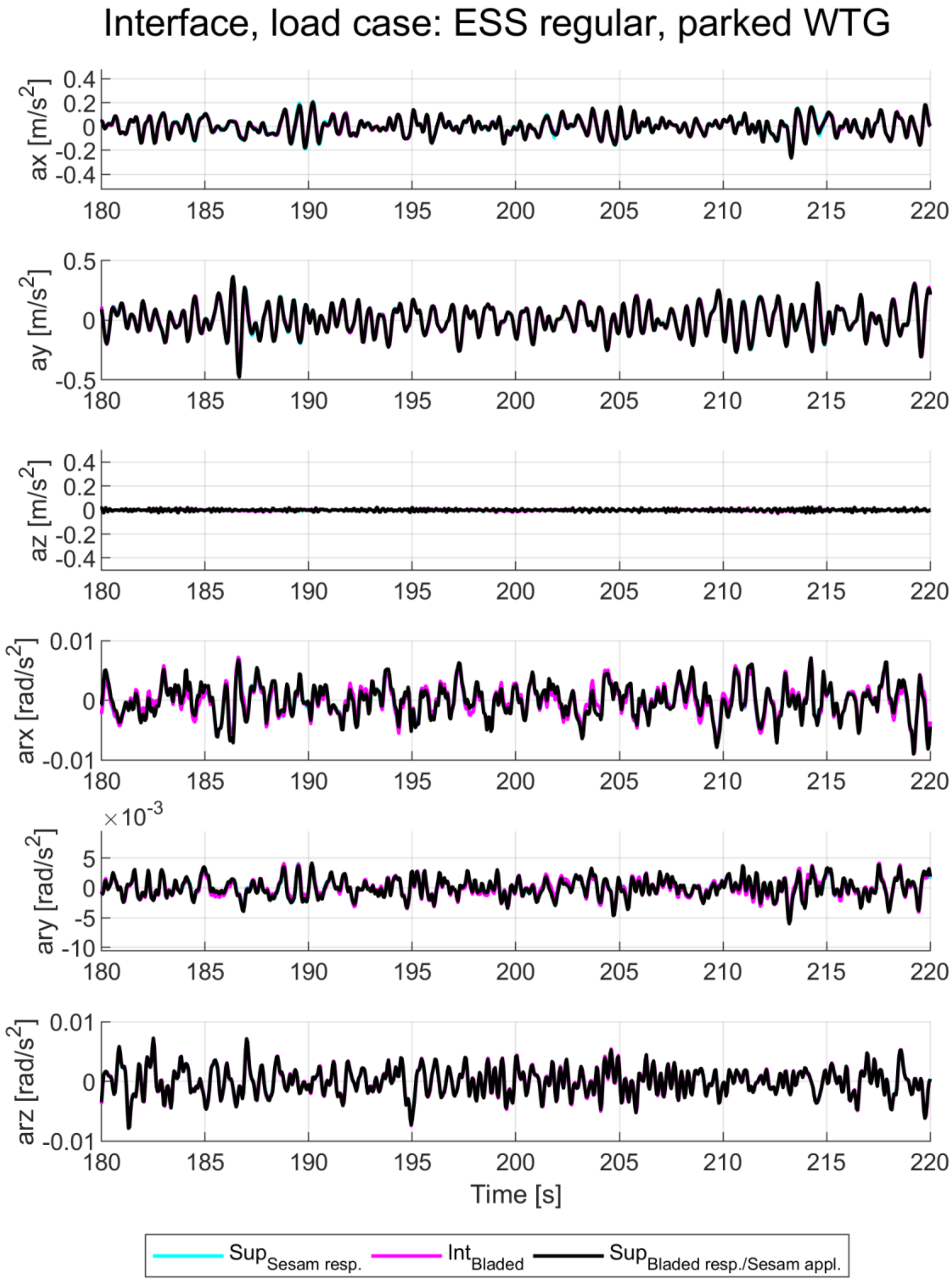


Figure 8-42 Accelerations at the interface around 200 s for the extreme load case with regular wave.

8.6.3 Jacket displacements due to wave and wind loading

Displacements are compared for the joints in the jacket as indicated in Figure 8-6. The displacements are extracted from two analyses, being the retracking superelement run in Sesam (which uses the interface loads obtained from the superelement analysis in Bladed) and the integrated Bladed analysis. No Bladed superelement results are included, because the superelement run in Bladed does not have the actual jacket present.

The wave and wind that are modelled in the simulations are running along the x-axis in the positive direction of the global coordinate system. The displacements have therefore been extracted at joints on the negative x-side of the model, i.e. on the side of the jacket that sees the incoming wave and wind first. Two joints are selected near the top of the jacket (one K-joint and one X-joint) and two near the bottom of the jacket. The positions are indicated in Figure 8-6.

The jacket displacements are shown in sections 8.6.3.1, 8.6.3.2 and 8.6.3.3 for the constrained wave, irregular wave and regular wave respectively. In general, the results match well between the Bladed integrated and Sesam retracking superelement analysis. The jacket nodal displacements for some of the selected joints show some difference for the constrained wave case for dx and dry (both due to wave loading in the main loading direction, mainly visible for the X-braces and for the upper K-joint) and for dz (mainly for joint Jt_K_5_4, and reducing when moving upwards along the jacket). This could be expected, as the same can be seen for the displacements at the interface for the constrained wave case in section 8.6.2. The same explanation applies here, i.e. the differences occur for the time intervals at which the constrained wave peaks occur, due to the difference in wave theory there. For the irregular and regular wave cases, which use the same wave theories in both Sesam and Bladed, there is only some difference visible for dx in joint Jt_K_5_4 and dry in joint Jt_X_4_3 (both in the bottom of the jacket), but besides that the differences between Sesam and Bladed disappear.

8.6.3.1 Constrained wave

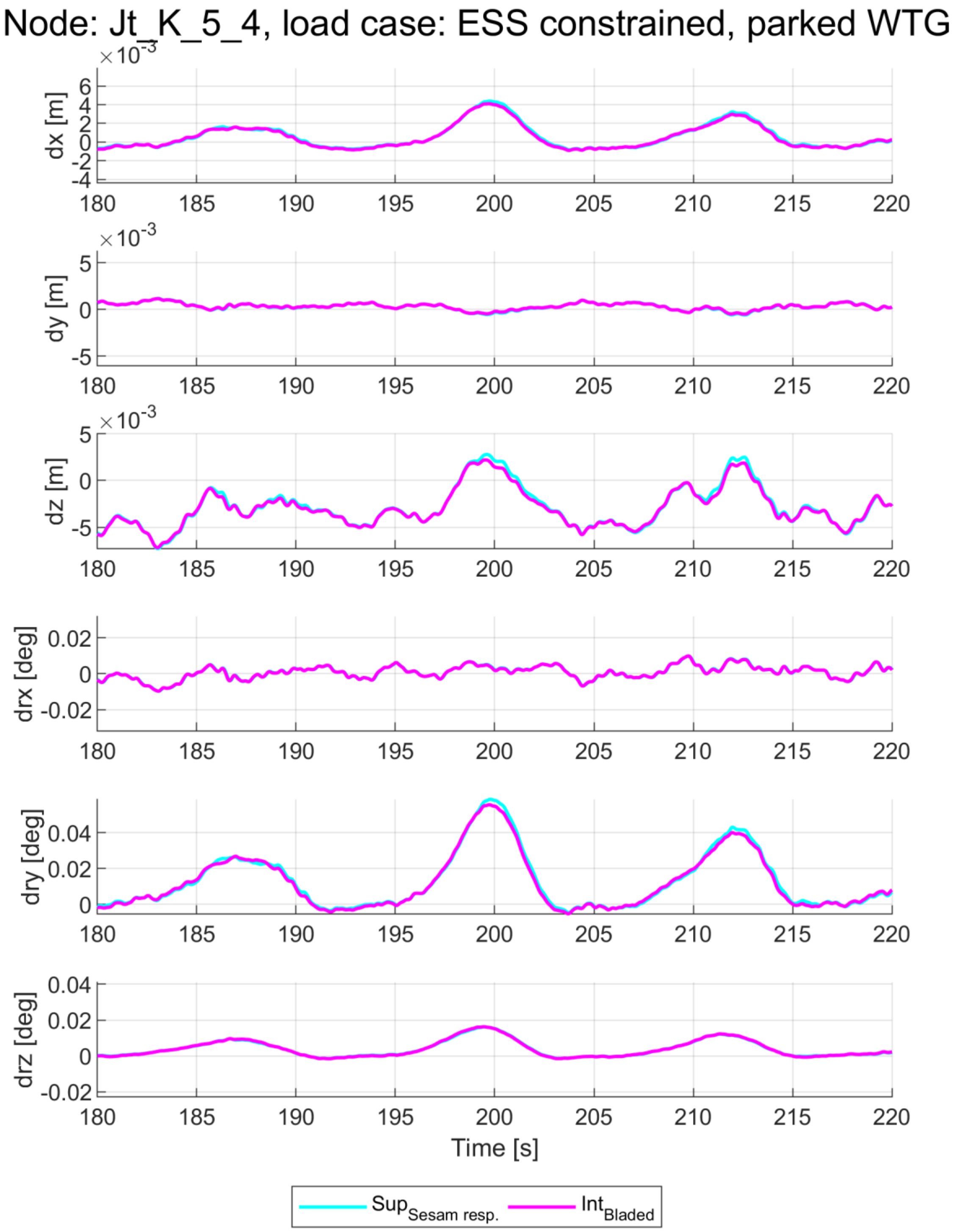


Figure 8-43 Displacement and rotation at joint Jt_K_5_4 around 200 s for the extreme load case with constrained wave.

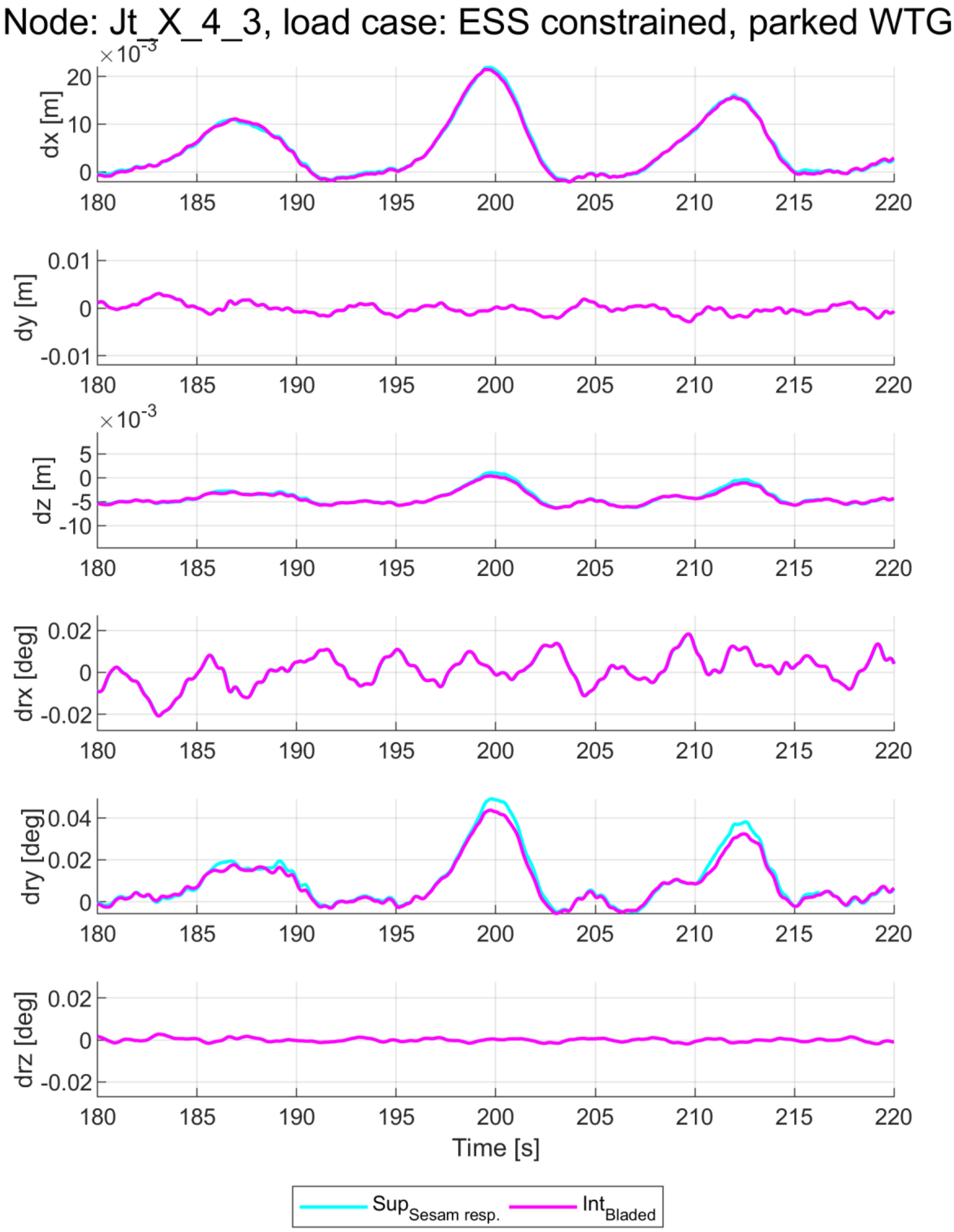


Figure 8-44 Displacement and rotation at joint Jt_X_4_3 around 200 s for the extreme load case with constrained wave.

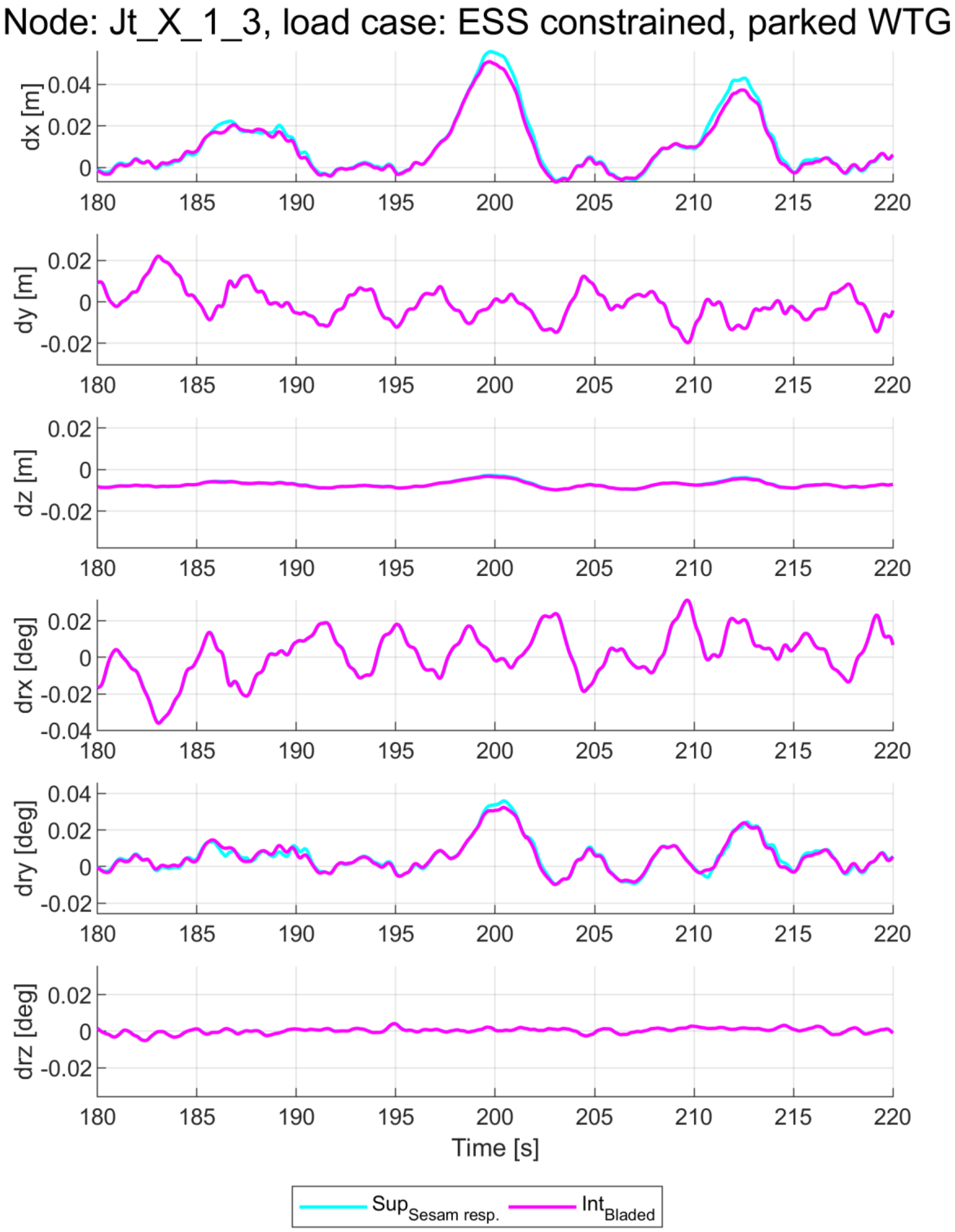


Figure 8-45 Displacement and rotation at joint Jt_X_1_3 around 200 s for the extreme load case with constrained wave.

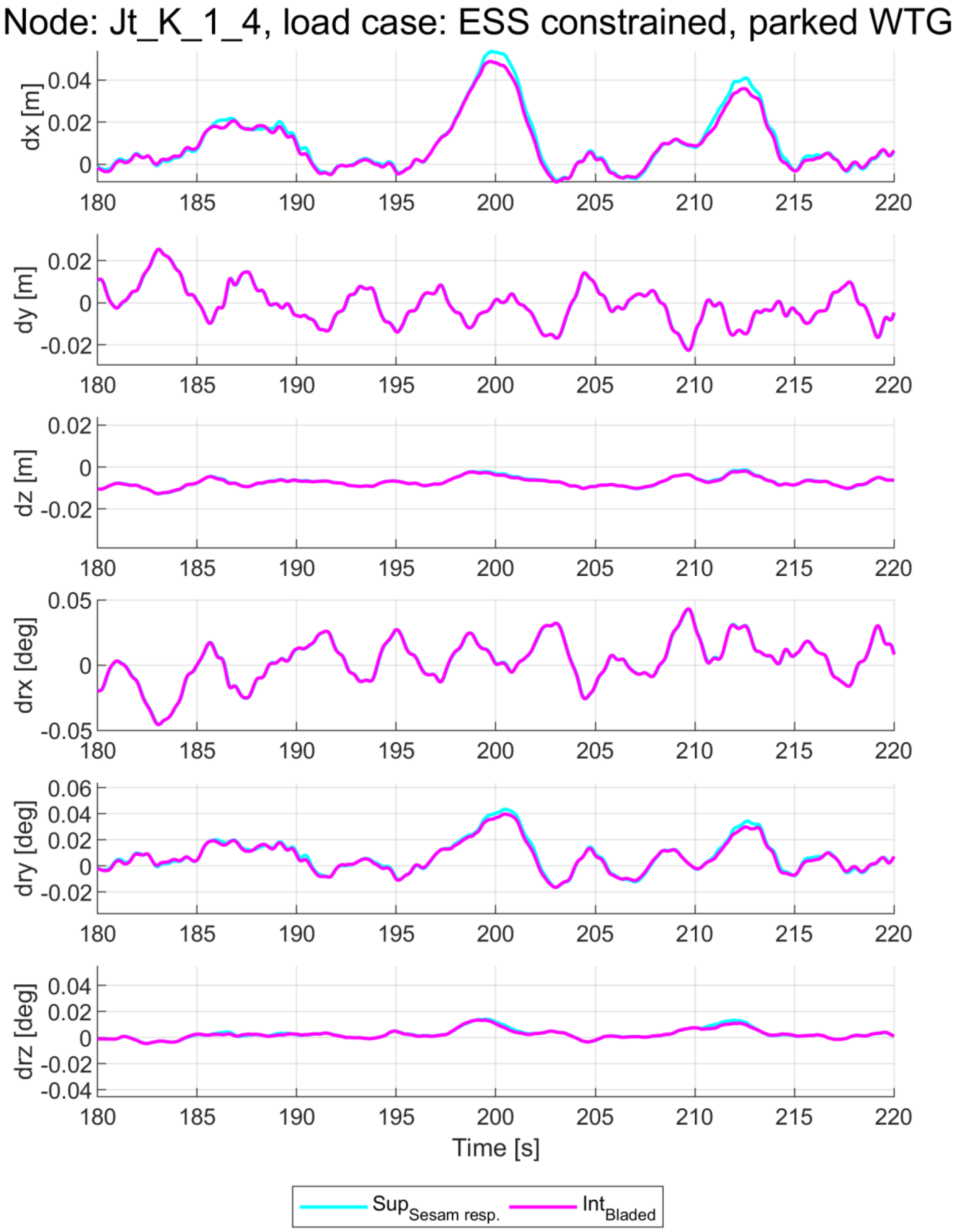


Figure 8-46 Displacement and rotation at joint Jt_K_1_4 around 200 s for the extreme load case with constrained wave.

8.6.3.2 Irregular wave

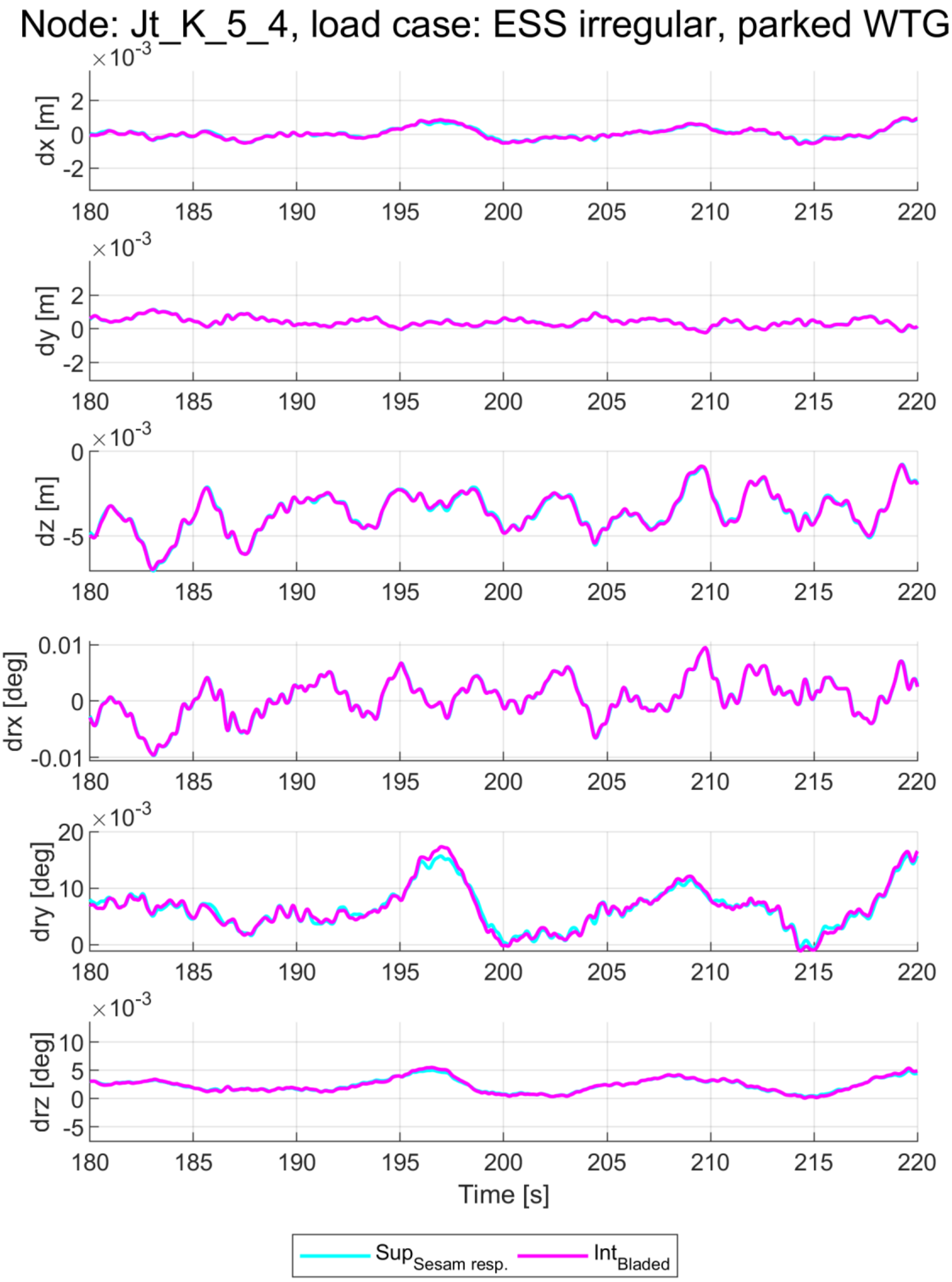


Figure 8-47 Displacement and rotation at joint Jt_K_5_4 around 200 s for the extreme load case with irregular wave.

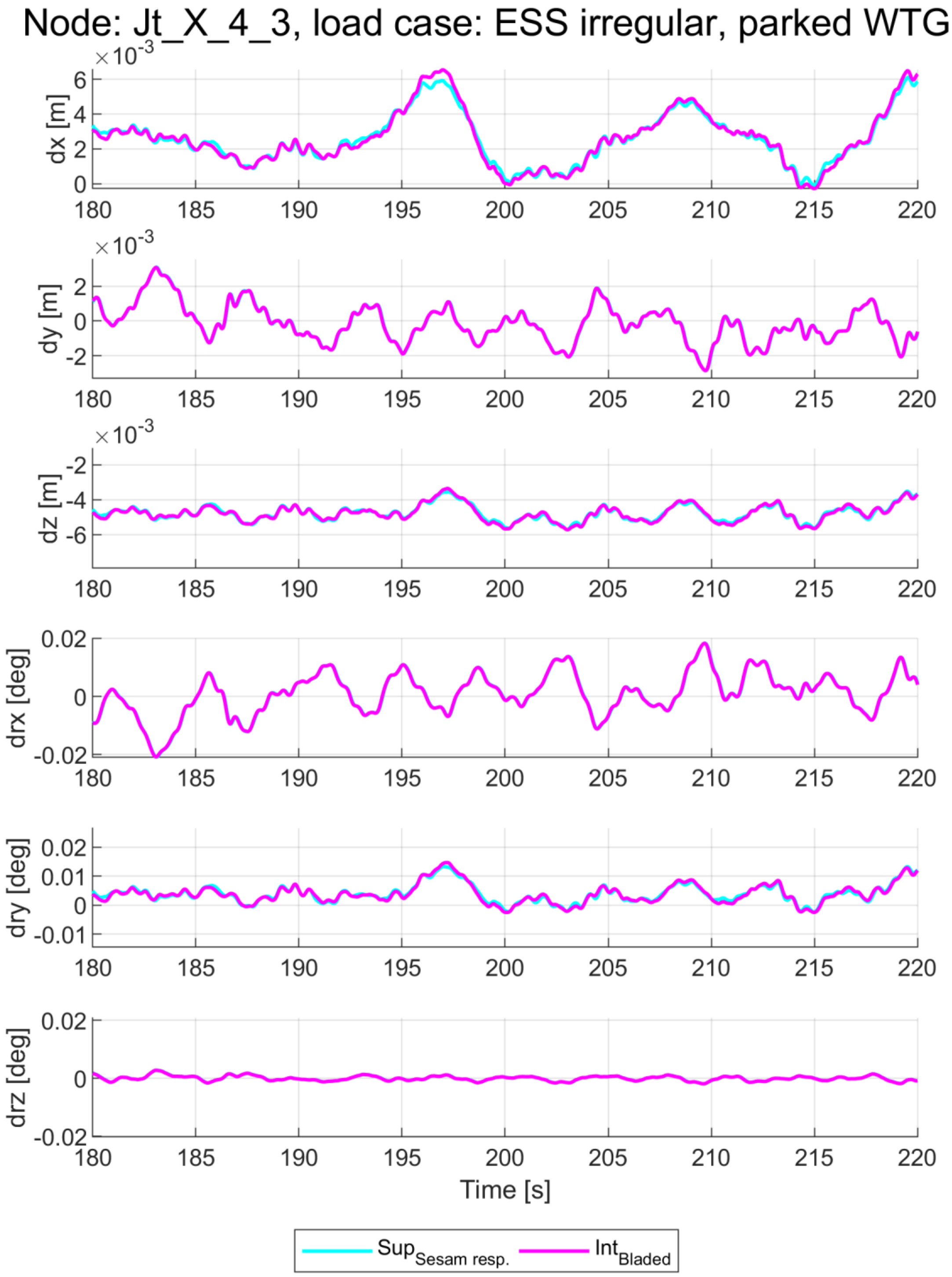


Figure 8-48 Displacement and rotation at joint Jt_X_4_3 around 200 s for the extreme load case with irregular wave.

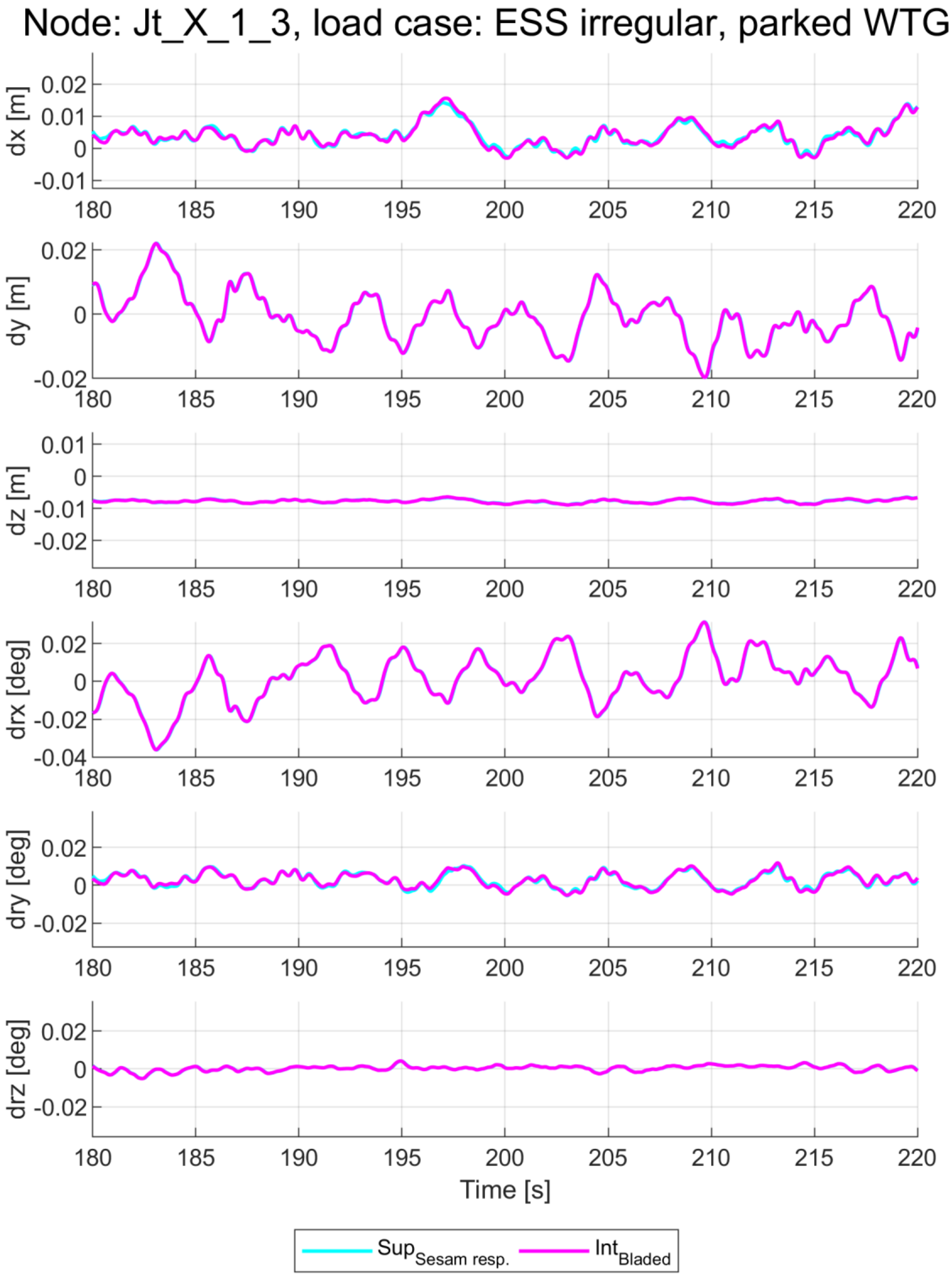


Figure 8-49 Displacement and rotation at joint Jt_X_1_3 around 200 s for the extreme load case with irregular wave.

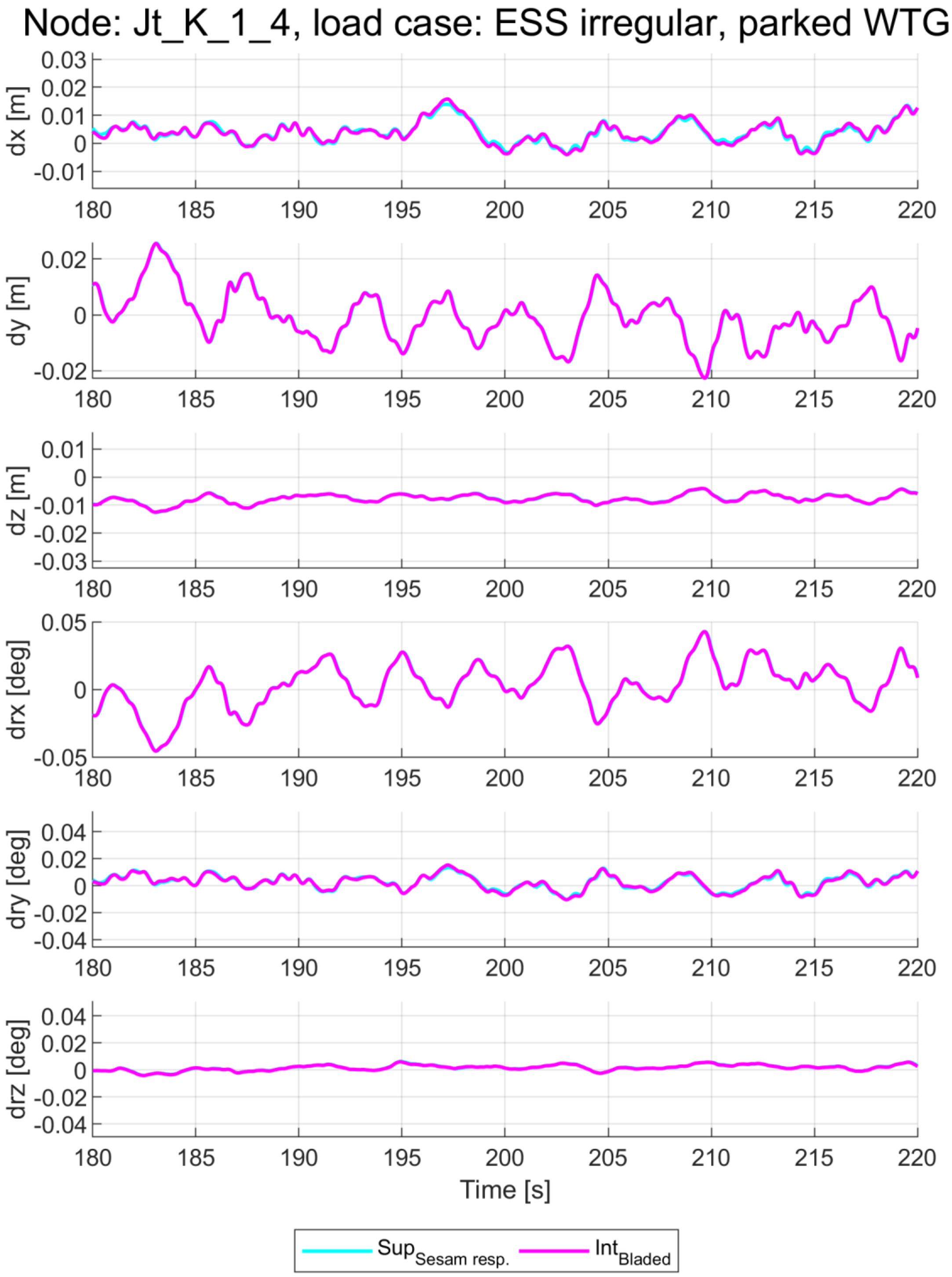


Figure 8-50 Displacement and rotation at joint Jt_K_1_4 around 200 s for the extreme load case with irregular wave.

8.6.3.3 Regular wave

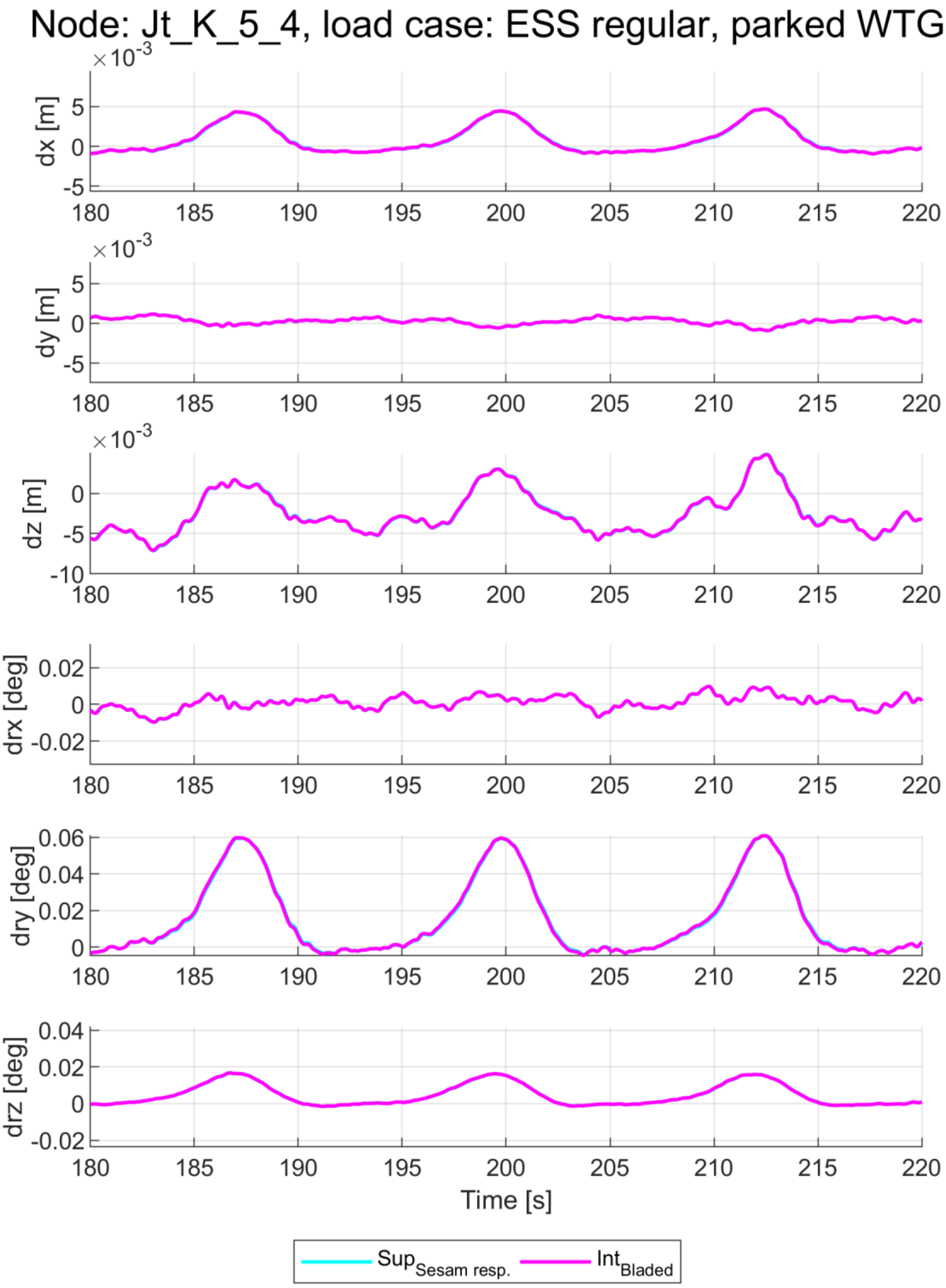


Figure 8-51 Displacement and rotation at joint Jt_K_5_4 around 200 s for the extreme load case with regular wave.

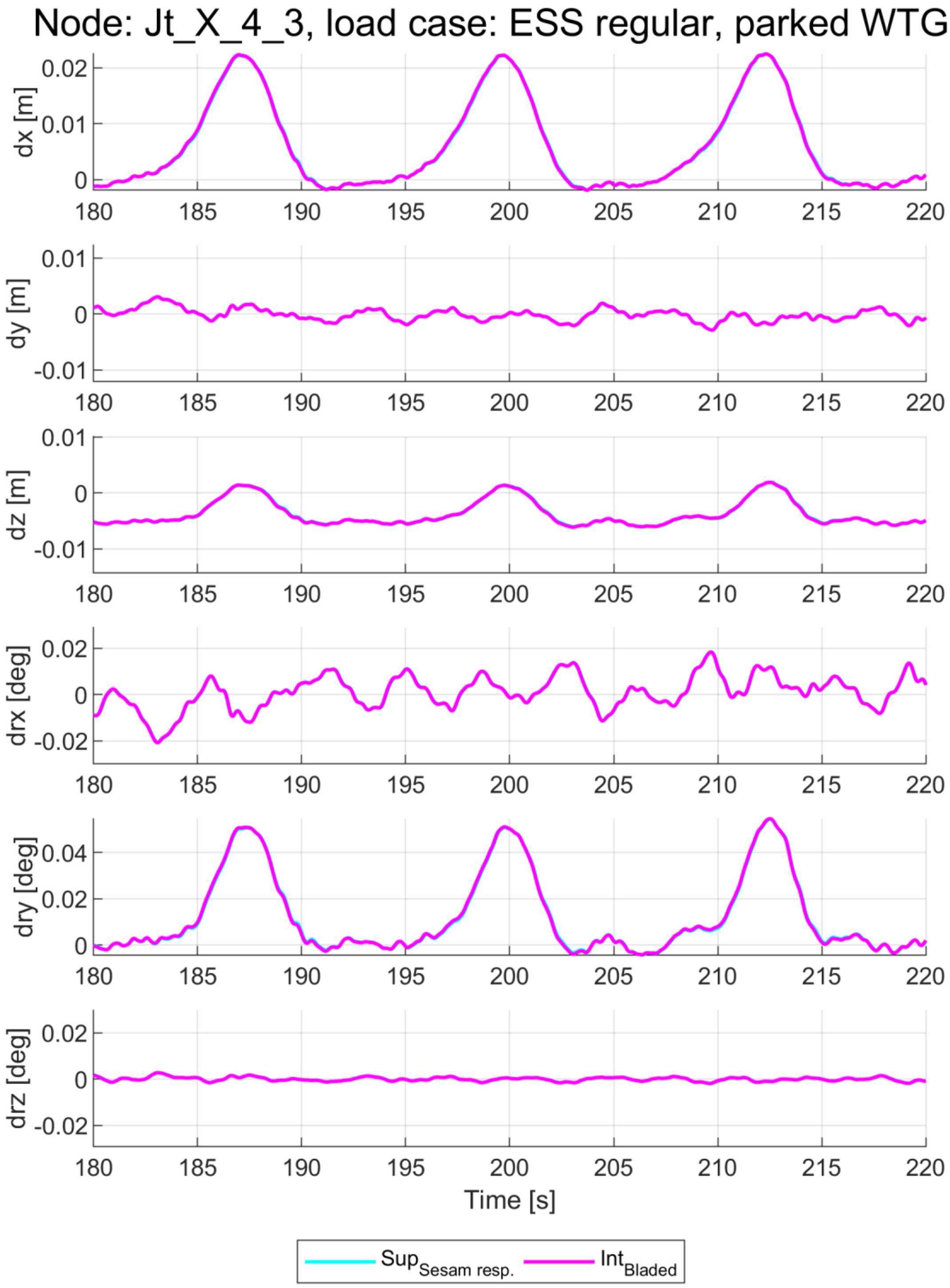


Figure 8-52 Displacement and rotation at joint Jt_X_4_3 around 200 s for the extreme load case with regular wave.

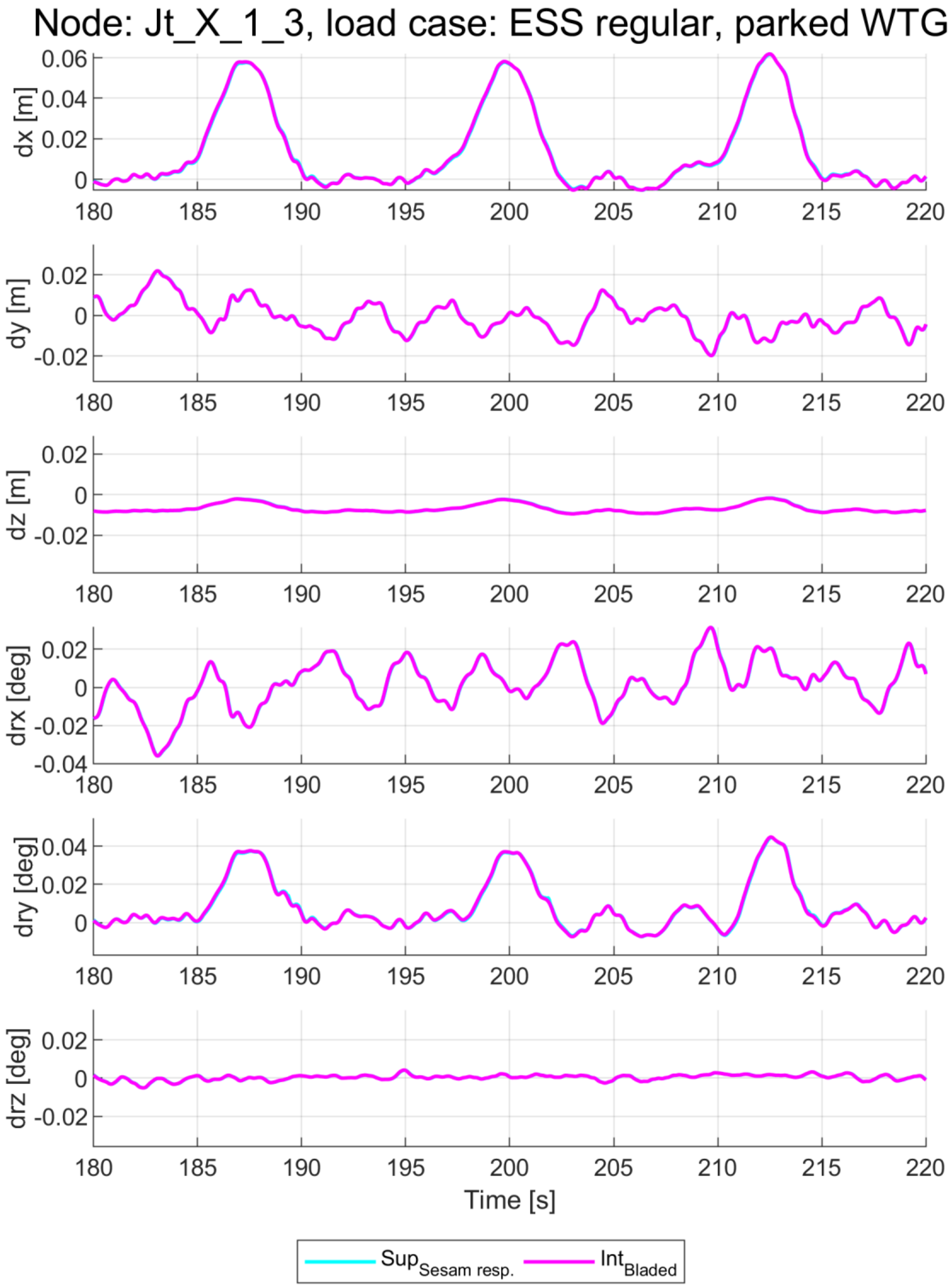


Figure 8-53 Displacement and rotation at joint Jt_X_1_3 around 200 s for the extreme load case with regular wave.

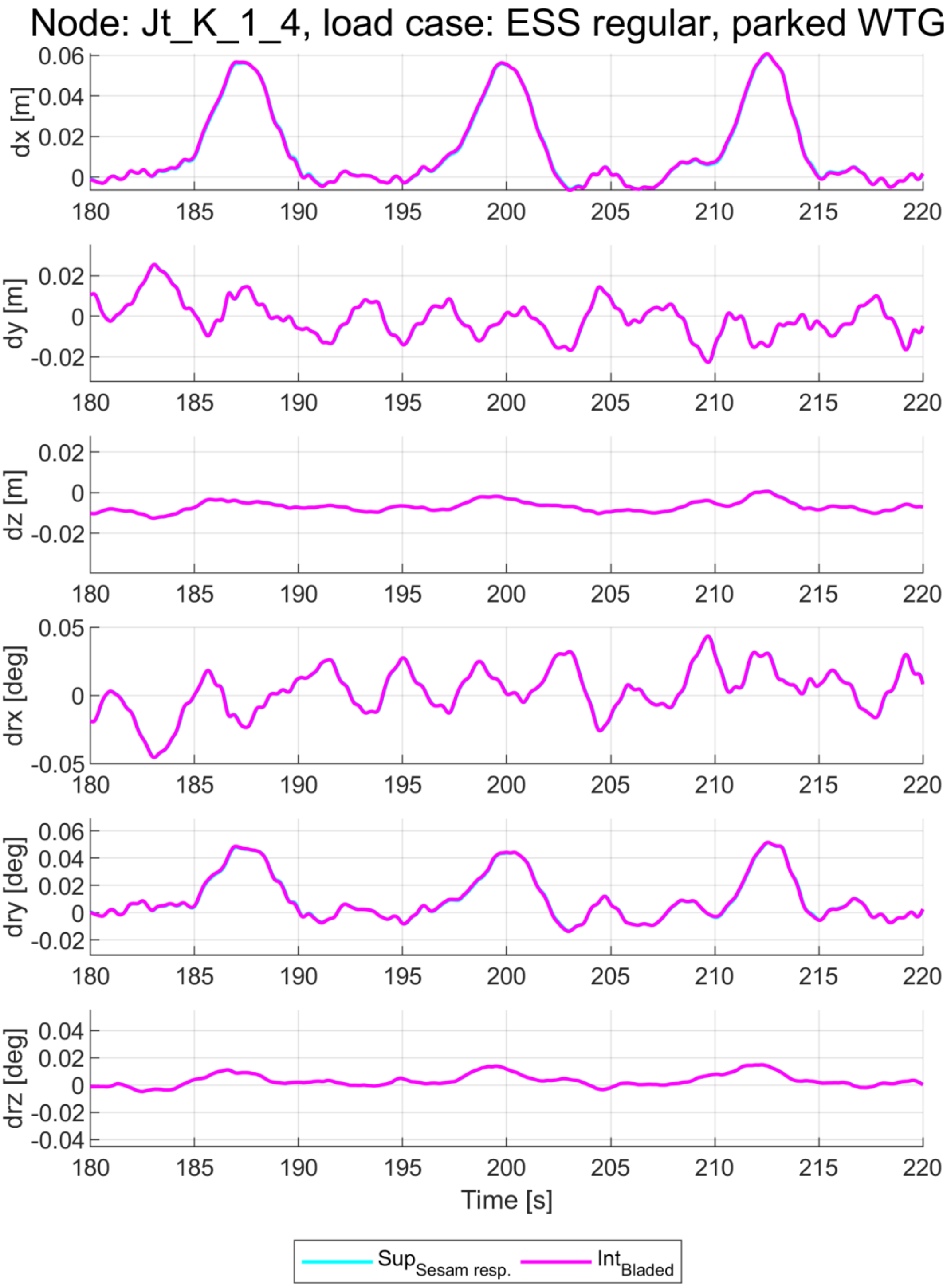


Figure 8-54 Displacement and rotation at joint Jt_K_1_4 around 200 s for the extreme load case with regular wave.

8.6.4 Jacket X-brace loads

A load comparison is performed for the braces connecting at the X-joint at the top of the structure, i.e. Jt_X_1_3. The forces and moments are compared in the four elements that are connecting at the joint, see Figure 8-22. The X-brace loads are shown in sections 8.6.4.1, 8.6.4.2 and 8.6.4.3 for the constrained wave, irregular wave and regular wave respectively.

As can be seen from the figures, the loads in the superelement model and in the integrated model compare well and are near-identical for most cases.

As expected, there is some difference in the case of the constrained wave (section 8.6.4.1), which is mainly visible for the bending moments Mx and My, and to a smaller degree in the other parameters. These occur near the peaks at and around the constrained wave and can be explained by the different wave theory used in recreating the wave in the integrated run in Bladed.

For the irregular case (section 8.6.4.2), some difference can be seen for the bending moment My (and somewhat for Mx too), occurring around the peaks in the surface elevation near 197 s and 220 s.

In the case of the regular wave (section 8.6.4.3), the results from Bladed and Sesam are near-identical.

8.6.4.1 Constrained wave

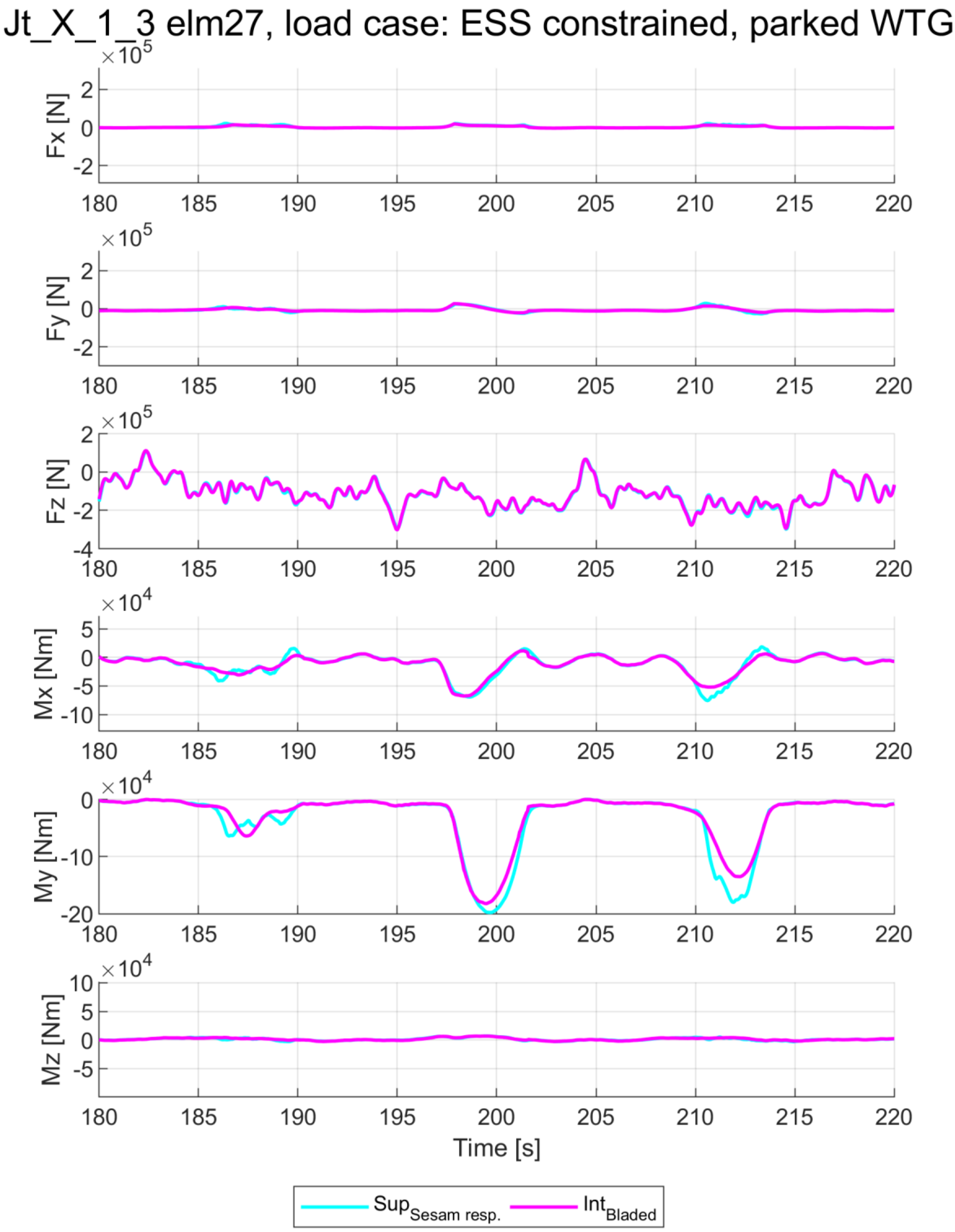


Figure 8-55 X-brace forces and moments at Jt_X_1_3, element 27, around 200 s for the extreme load case with constrained wave.

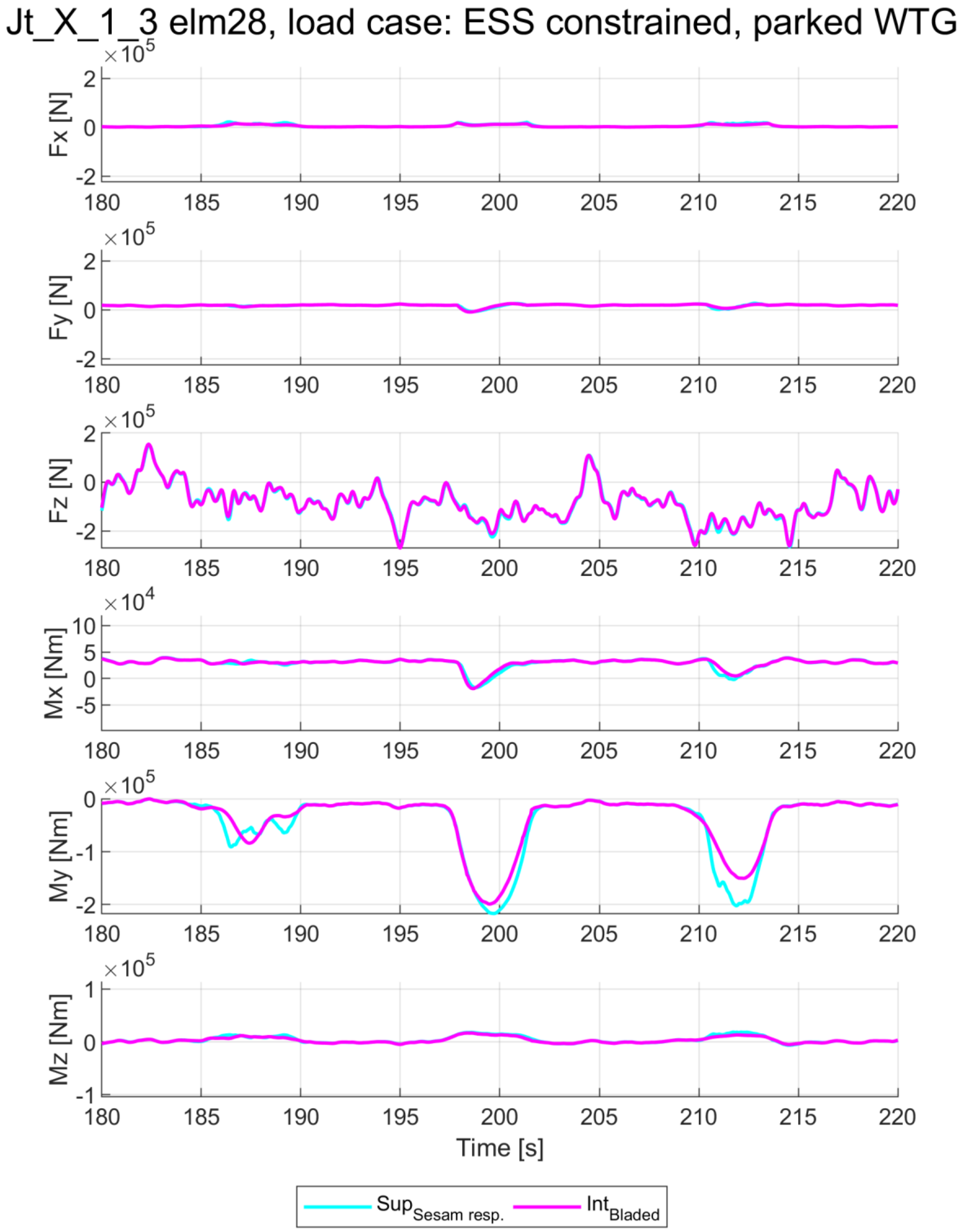


Figure 8-56 X-brace forces and moments at Jt_X_1_3, element 28, around 200 s for the extreme load case with constrained wave.

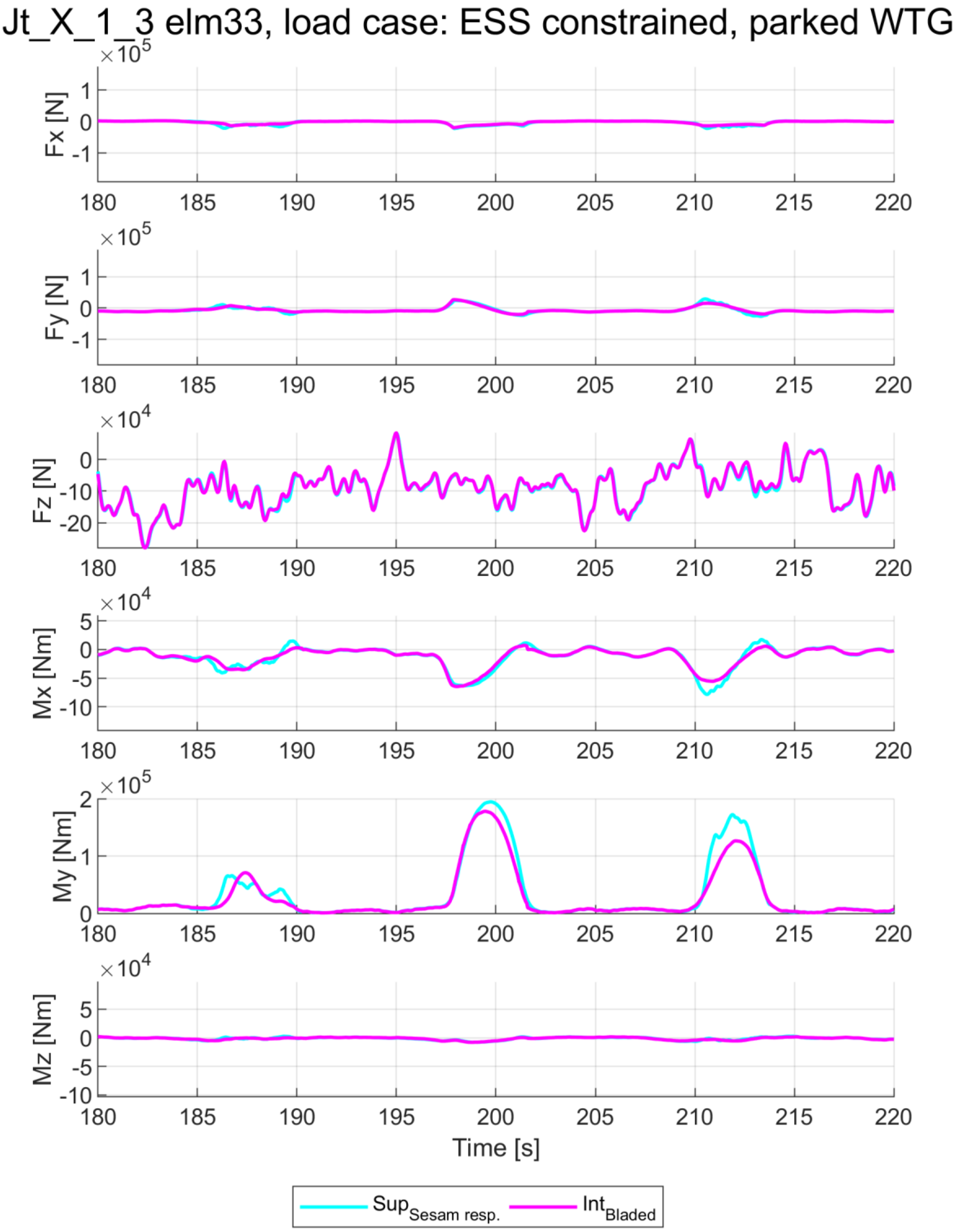


Figure 8-57 X-brace forces and moments at Jt_X_1_3, element 33, around 200 s for the extreme load case with constrained wave.

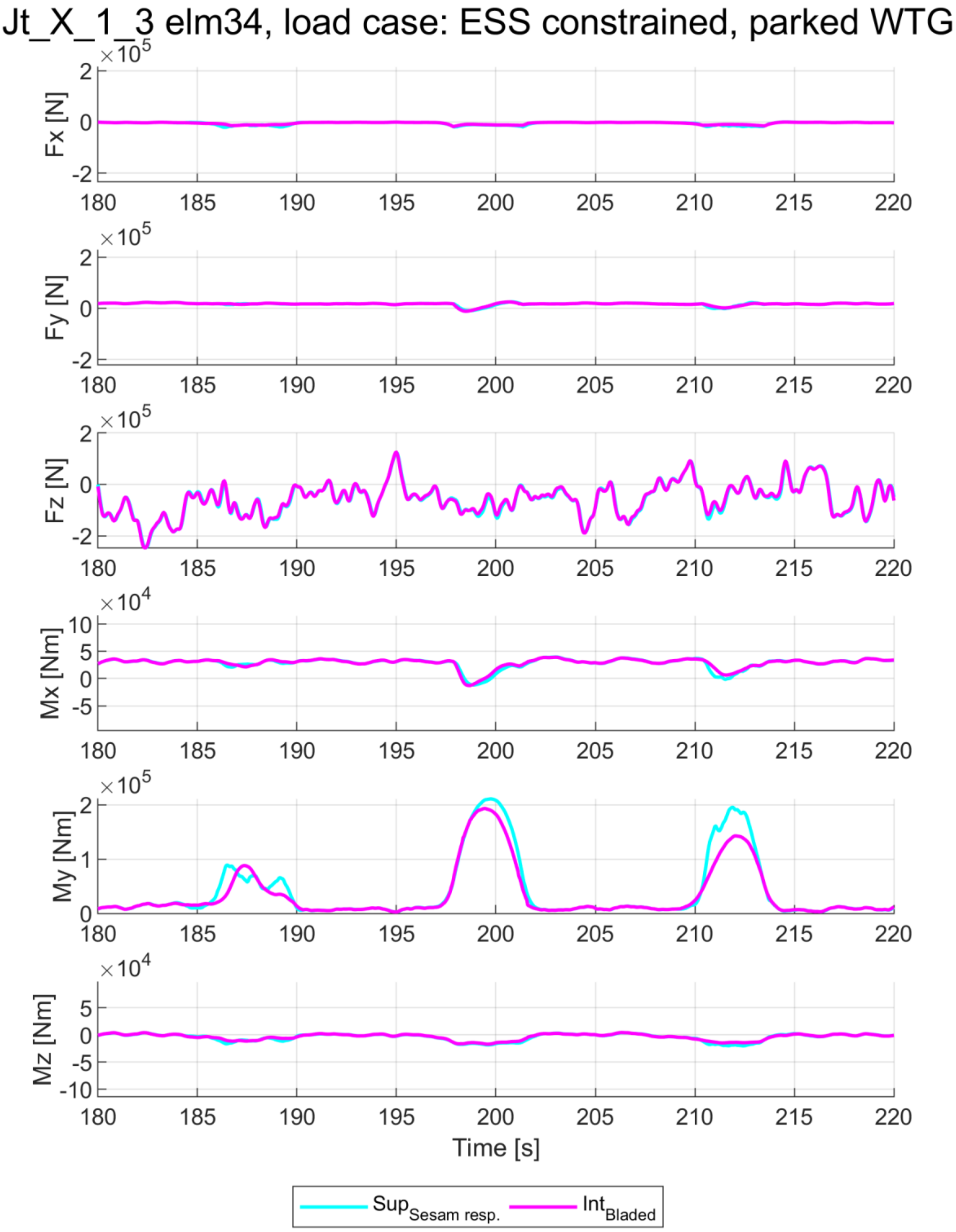


Figure 8-58 X-brace forces and moments at Jt_X_1_3, element 34, around 200 s for the extreme load case with constrained wave.

8.6.4.2 Irregular wave

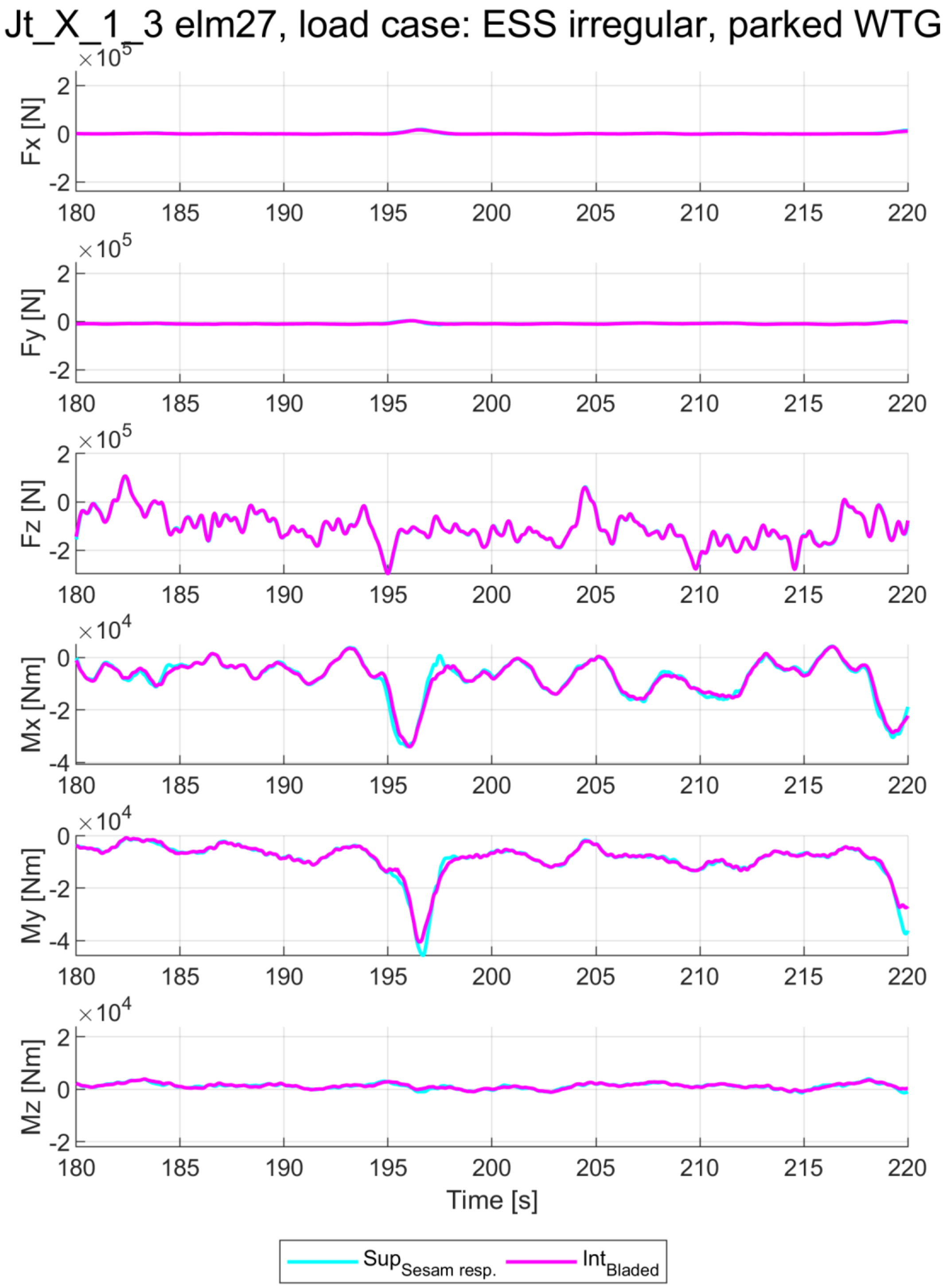


Figure 8-59 X-brace forces and moments at Jt_X_1_3, element 27, around 200 s for the extreme load case with irregular wave.

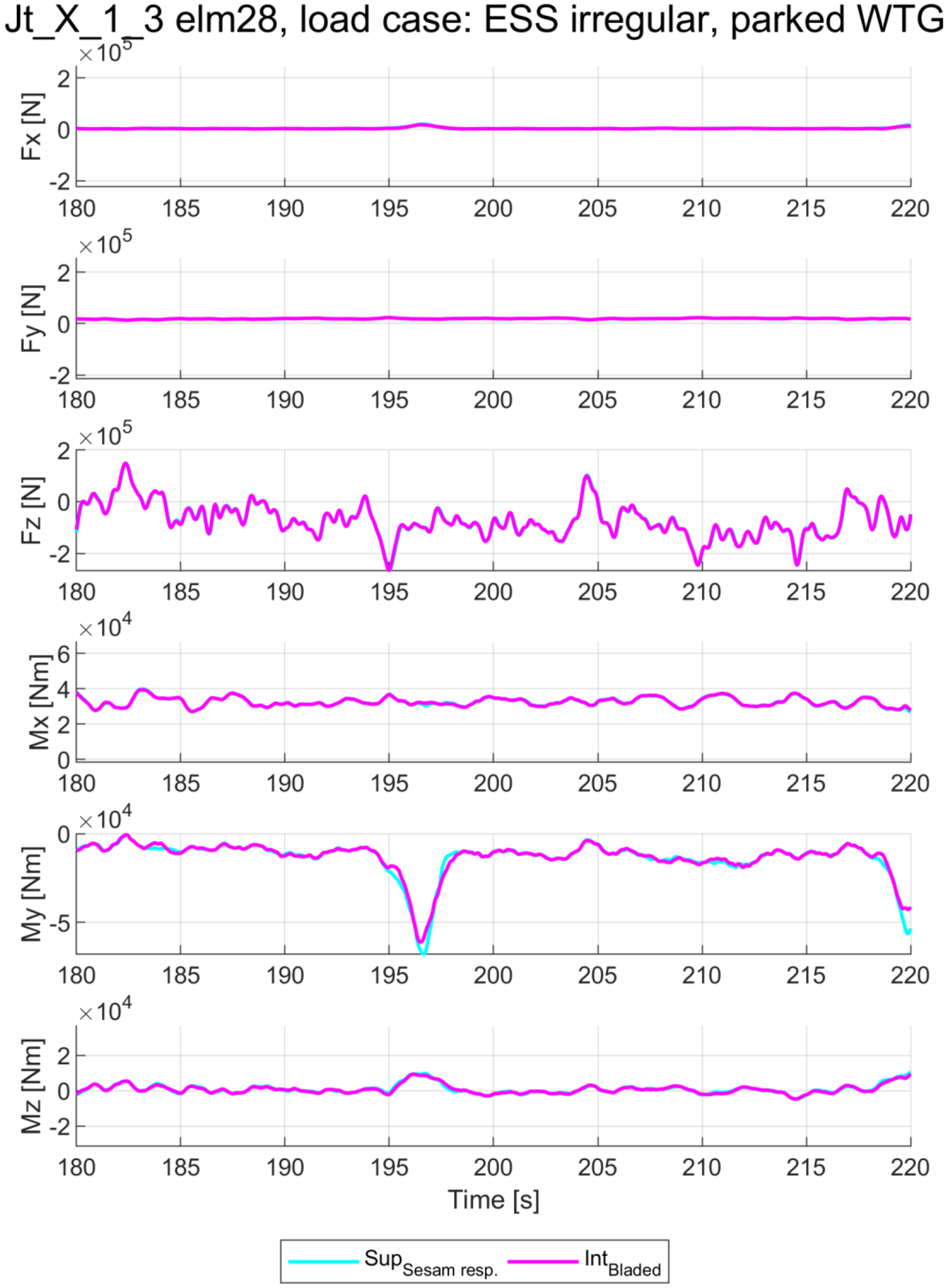


Figure 8-60 X-brace forces and moments at Jt_X_1_3, element 28, around 200 s for the extreme load case with irregular wave.

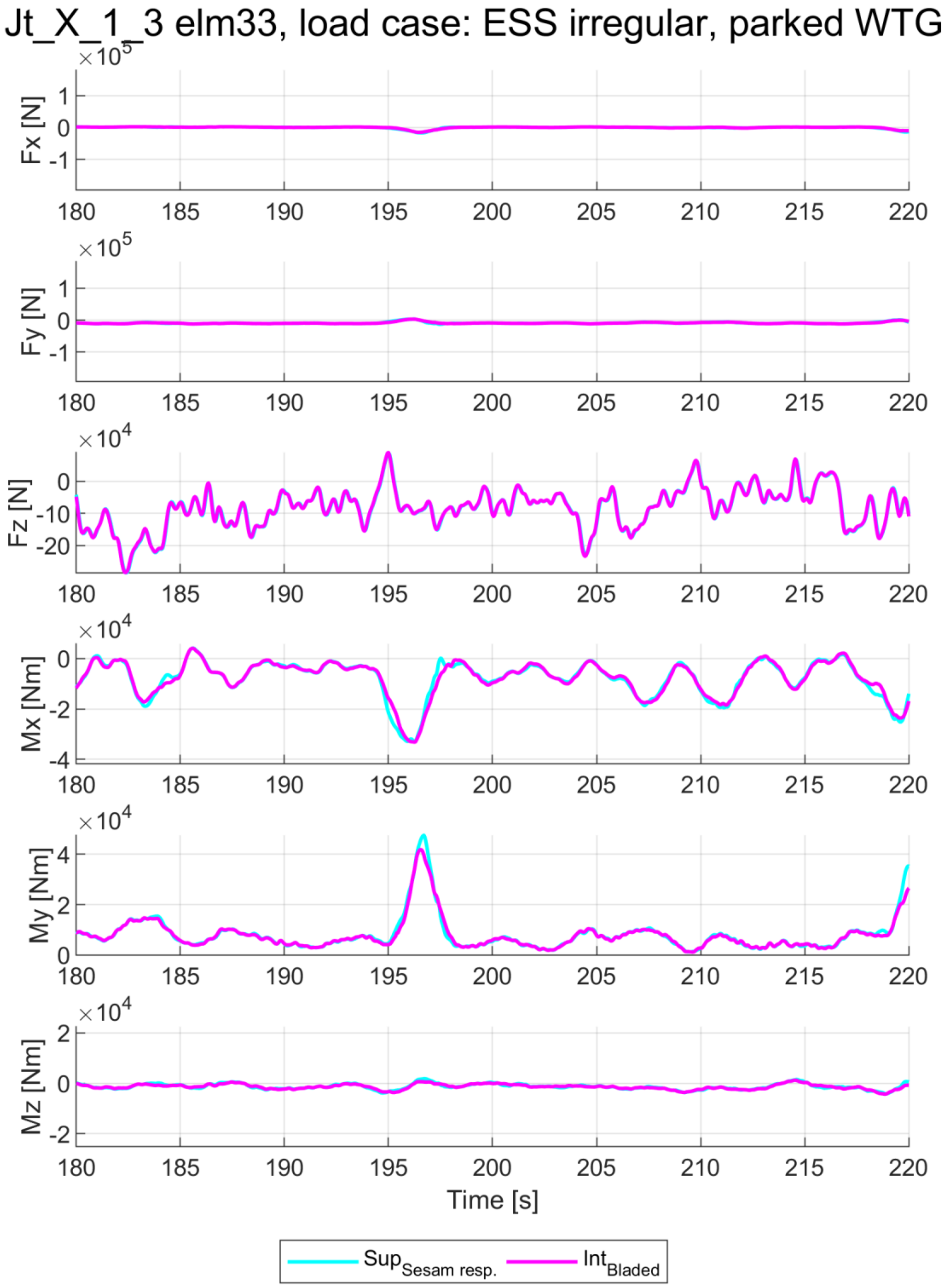


Figure 8-61 X-brace forces and moments at Jt_X_1_3, element 33, around 200 s for the extreme load case with irregular wave.

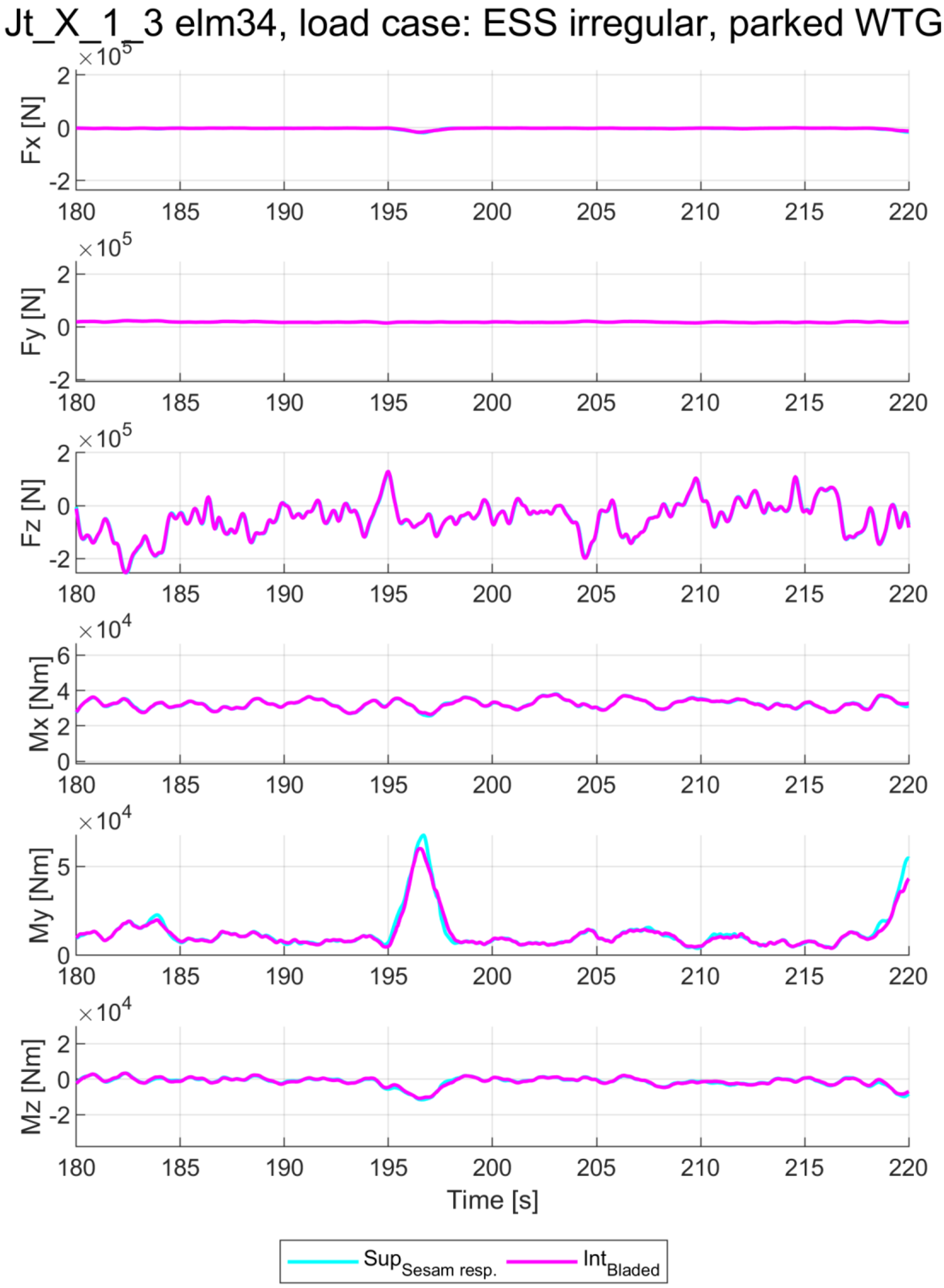


Figure 8-62 X-brace forces and moments at Jt_X_1_3, element 34, around 200 s for the extreme load case with irregular wave.

8.6.4.3 Regular wave

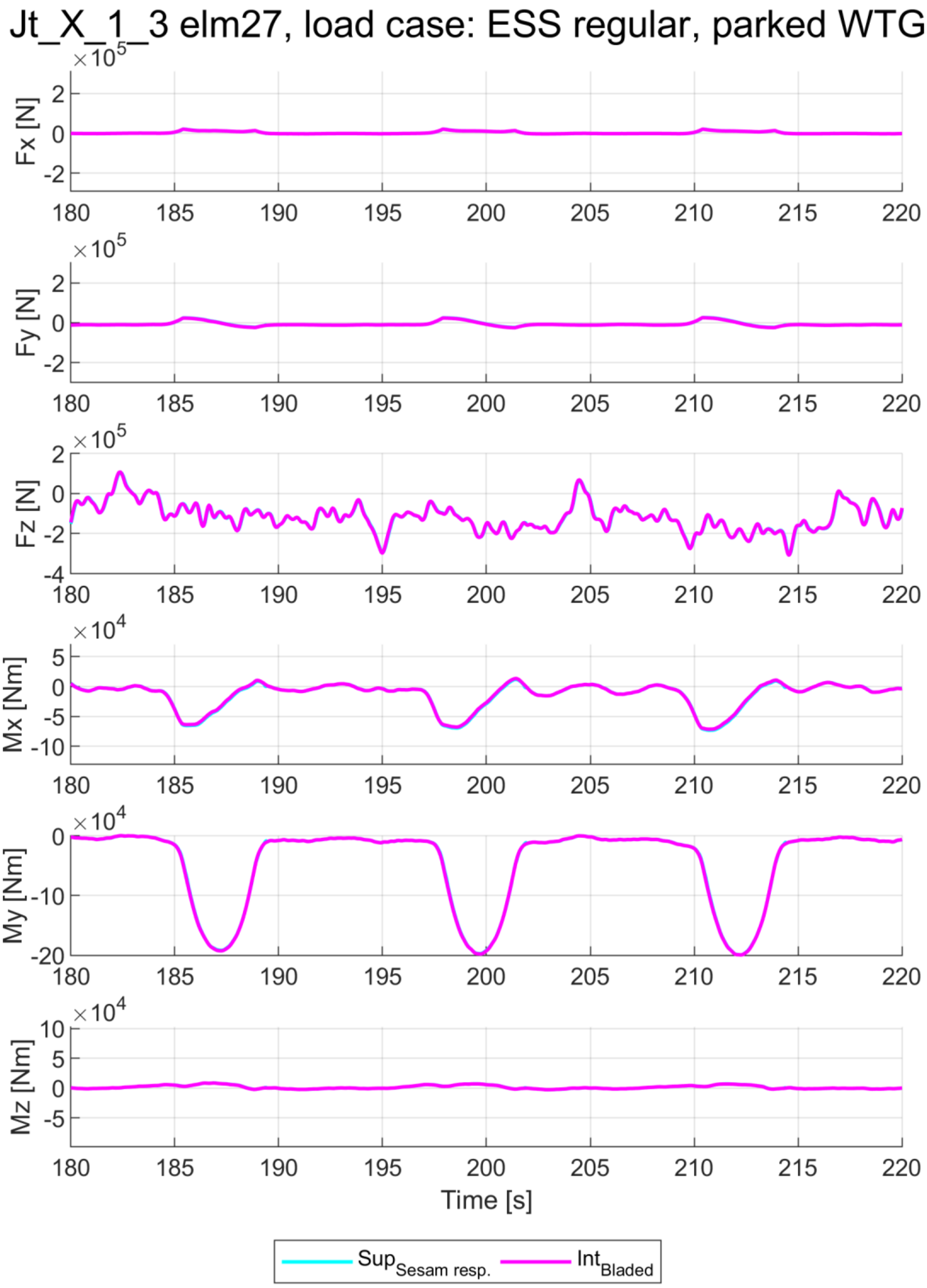


Figure 8-63 X-brace forces and moments at Jt_X_1_3, element 27, around 200 s for the extreme load case with regular wave.

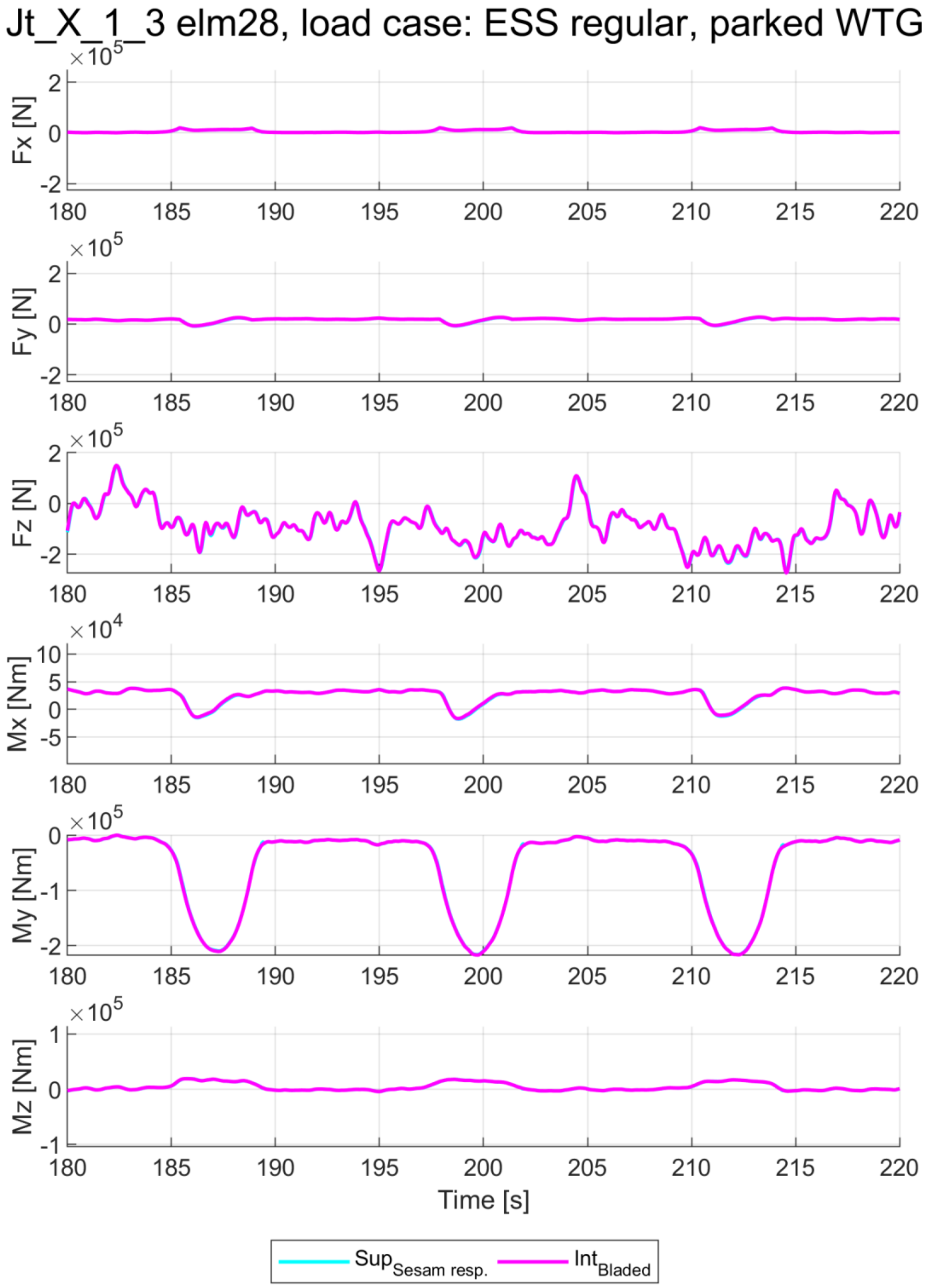


Figure 8-64 X-brace forces and moments at Jt_X_1_3, element 28, around 200 s for the extreme load case with regular wave.

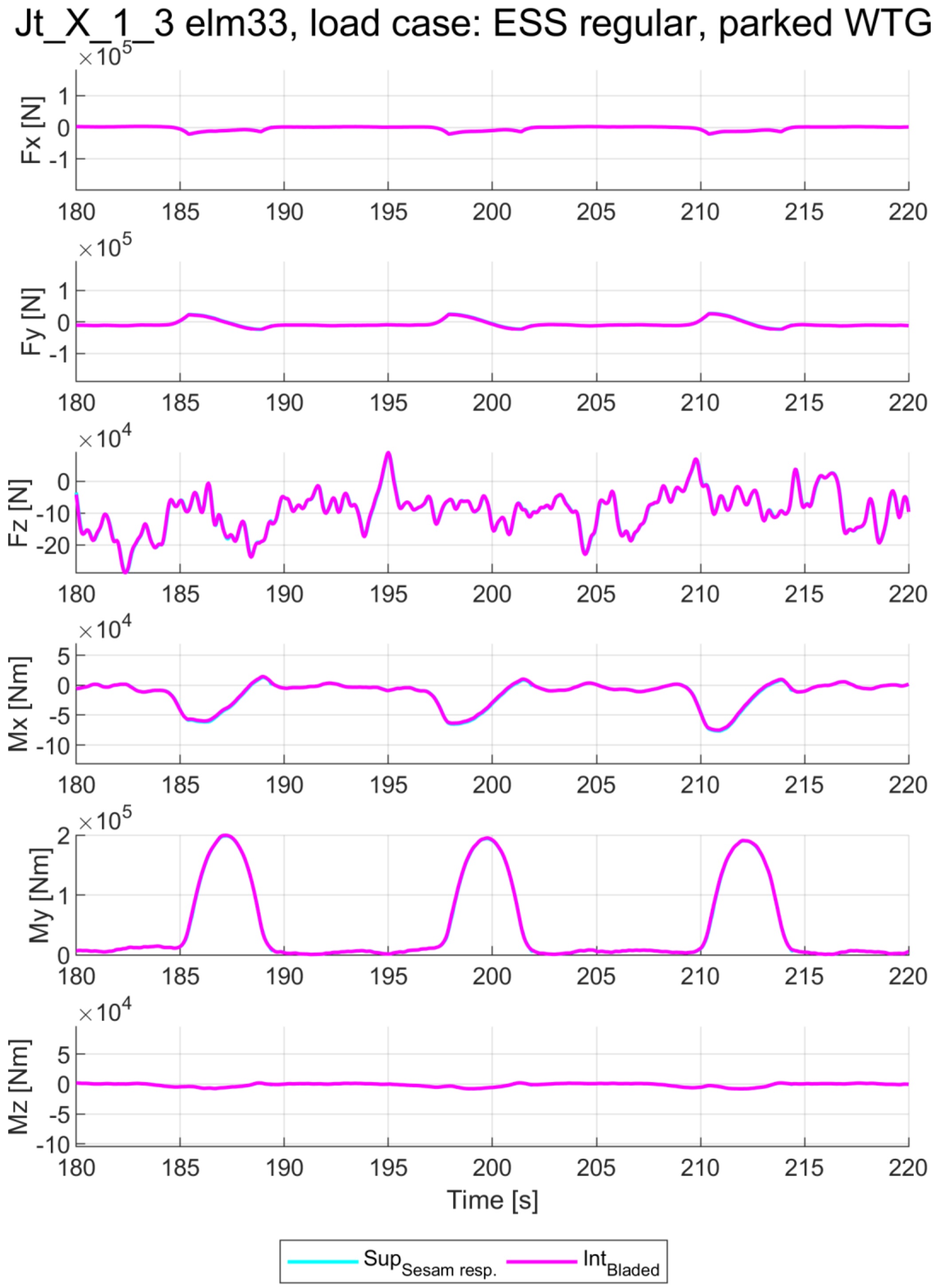


Figure 8-65 X-brace forces and moments at Jt_X_1_3, element 33, around 200 s for the extreme load case with regular wave.

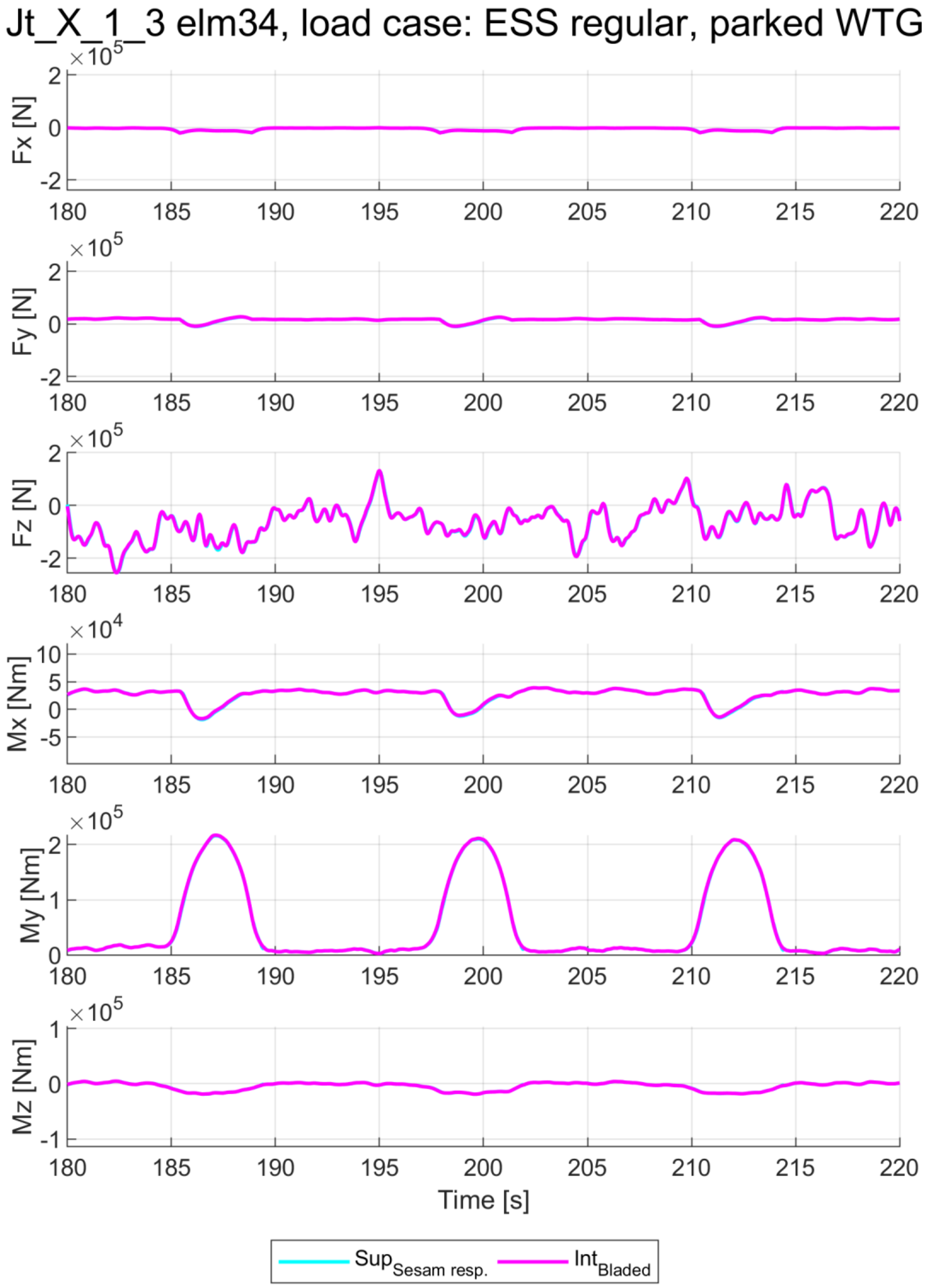


Figure 8-66 X-brace forces and moments at Jt_X_1_3, element 34, around 200 s for the extreme load case with regular wave.

8.6.5 Tower top motions due to wave and wind loading

In addition to results at the interface and at the jacket joints, the motions at the tower top are compared. These should give a good indication on how well the different models compare. 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. Results that compare well at the tower top should therefore give a good indication on how closely the system has been modelled in the different ways. The Bladed integrated model includes the wind turbine and jacket in a single model, whereas the superelement model is a combination of the Sesam superelement combined with the wind turbine in Bladed.

The tower top displacements, velocities and accelerations are shown in sections 8.6.5.1, 8.6.5.2 and 8.6.5.3 for the constrained wave, irregular wave and regular wave respectively. The displacements, velocities and accelerations compare well, and no significant differences are seen.

8.6.5.1 Constrained wave

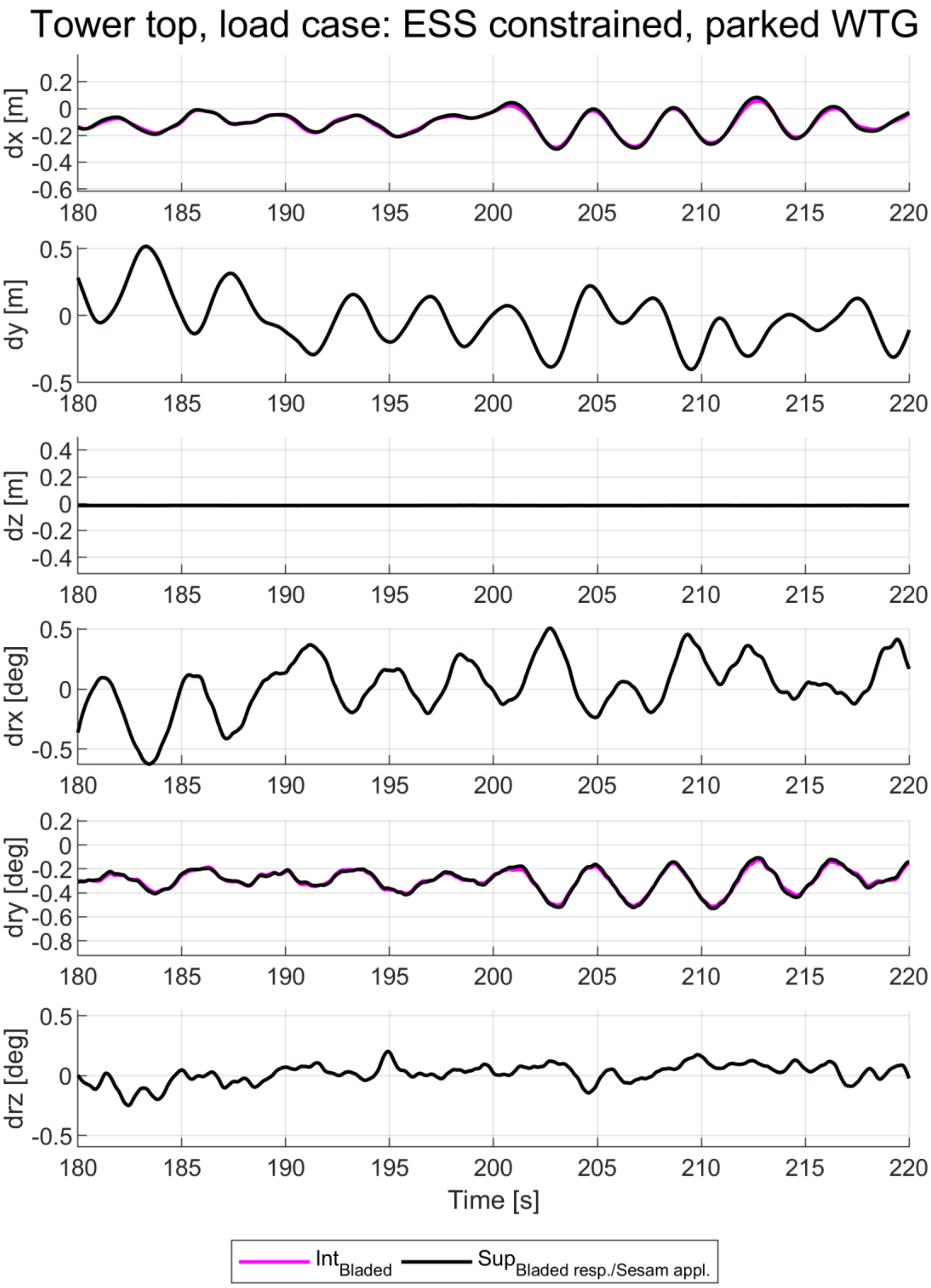


Figure 8-67 Displacements at the tower top around 200 s for the extreme load case with constrained wave.

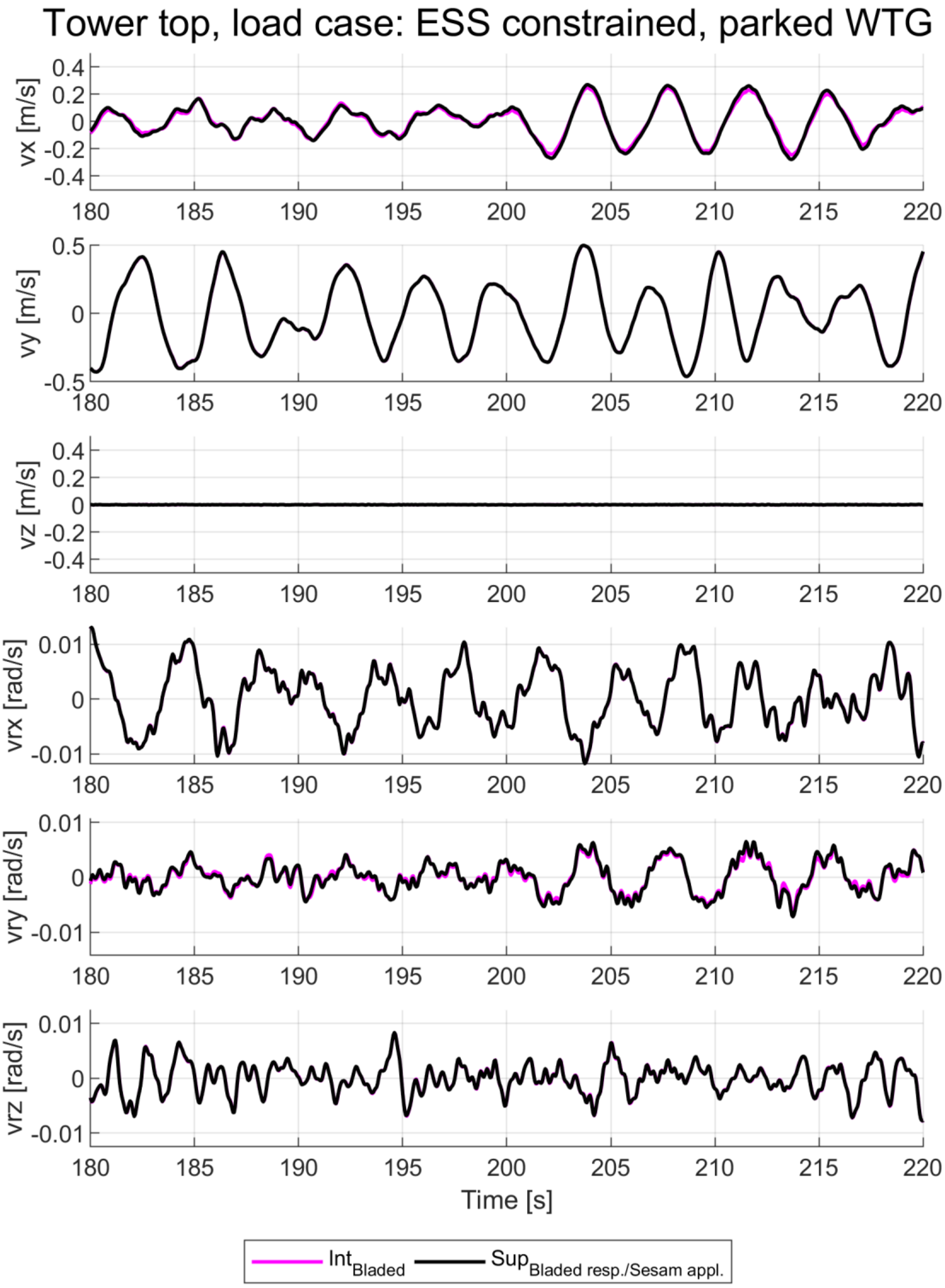


Figure 8-68 Velocities at the tower top around 200 s for the extreme load case with constrained wave.

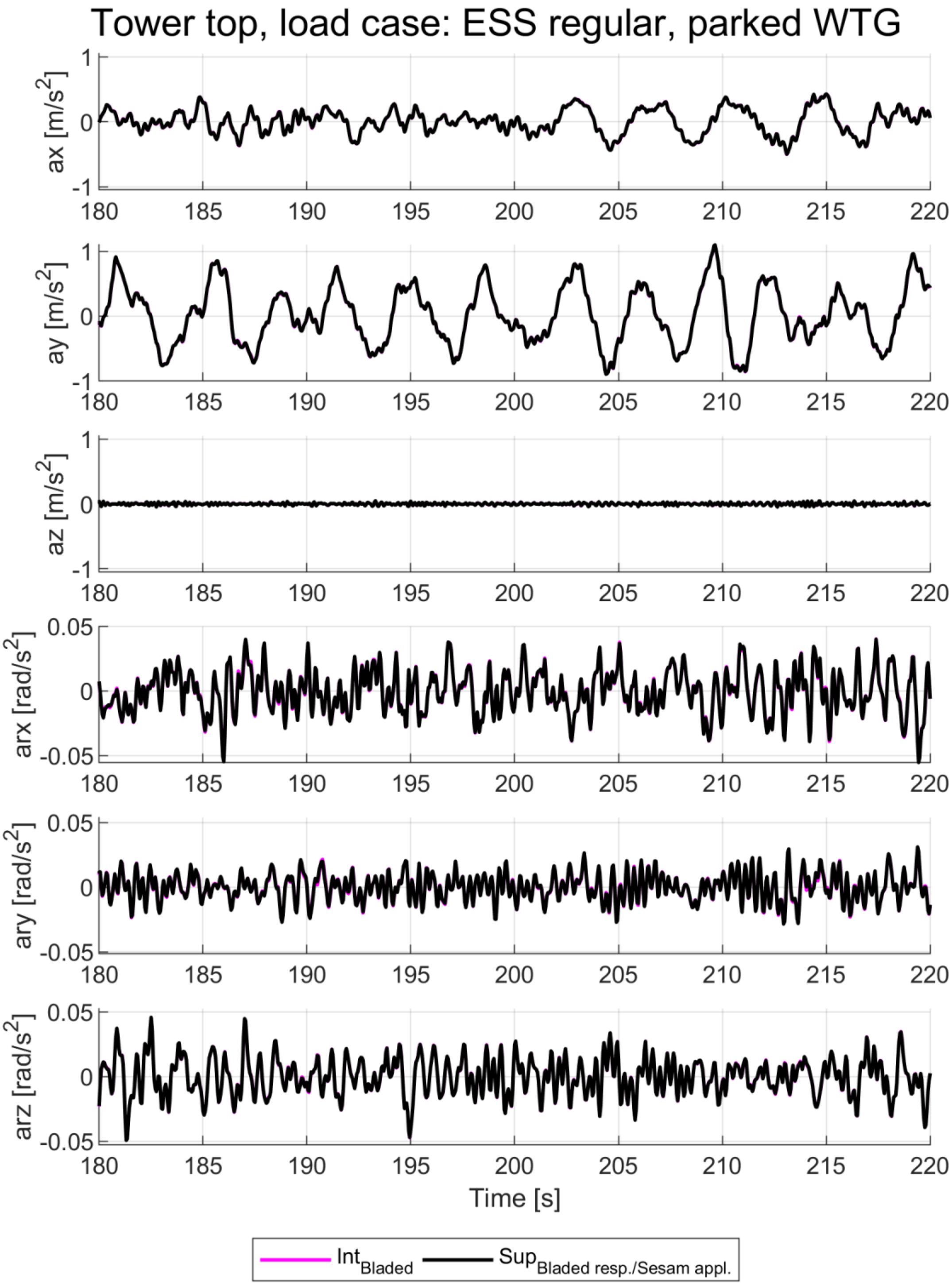


Figure 8-69 Accelerations at the tower top around 200 s for the extreme load case with constrained wave.

8.6.5.2 Irregular wave

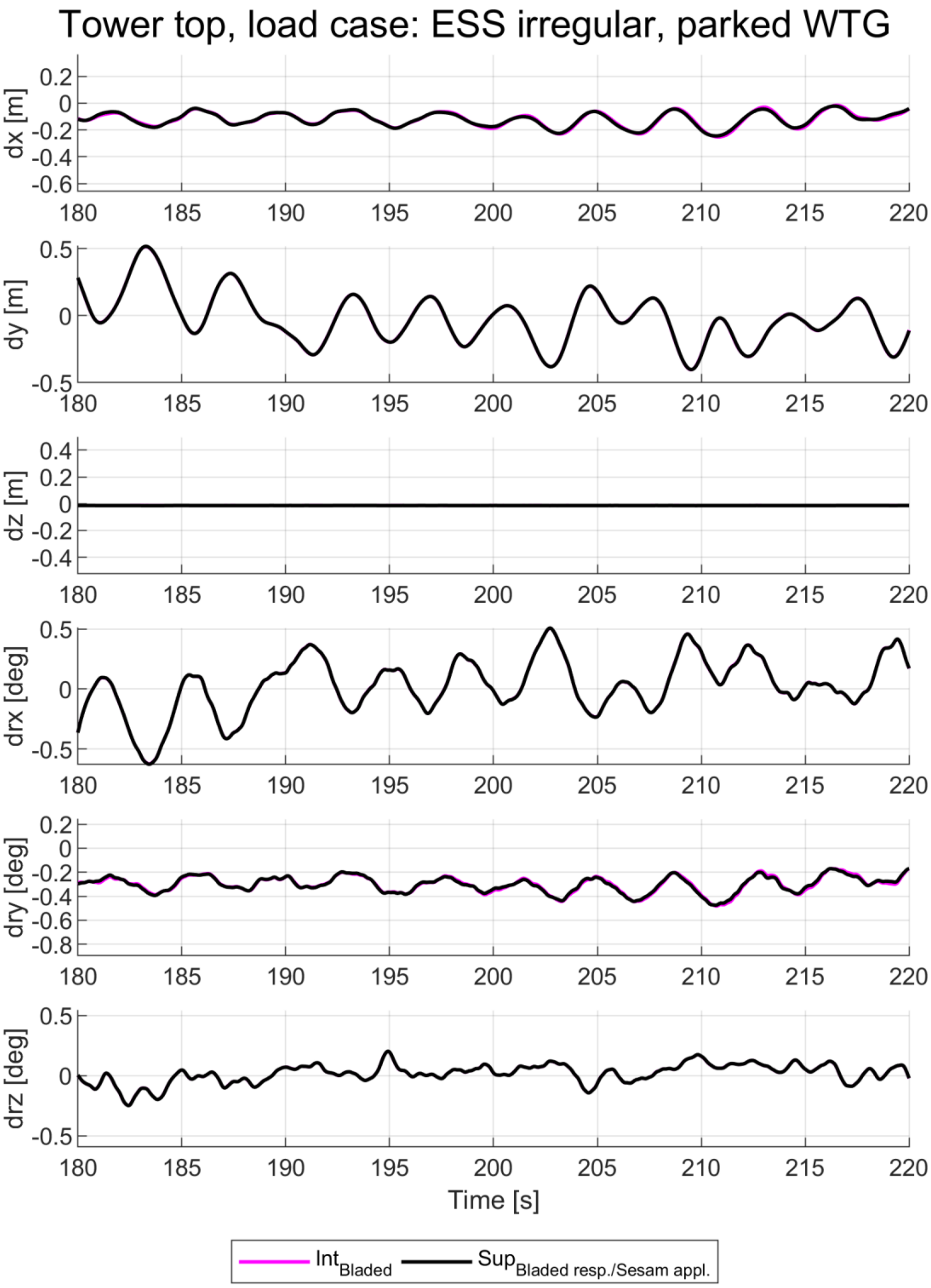


Figure 8-70 Displacements at the tower top around 200 s for the extreme load case with irregular wave.

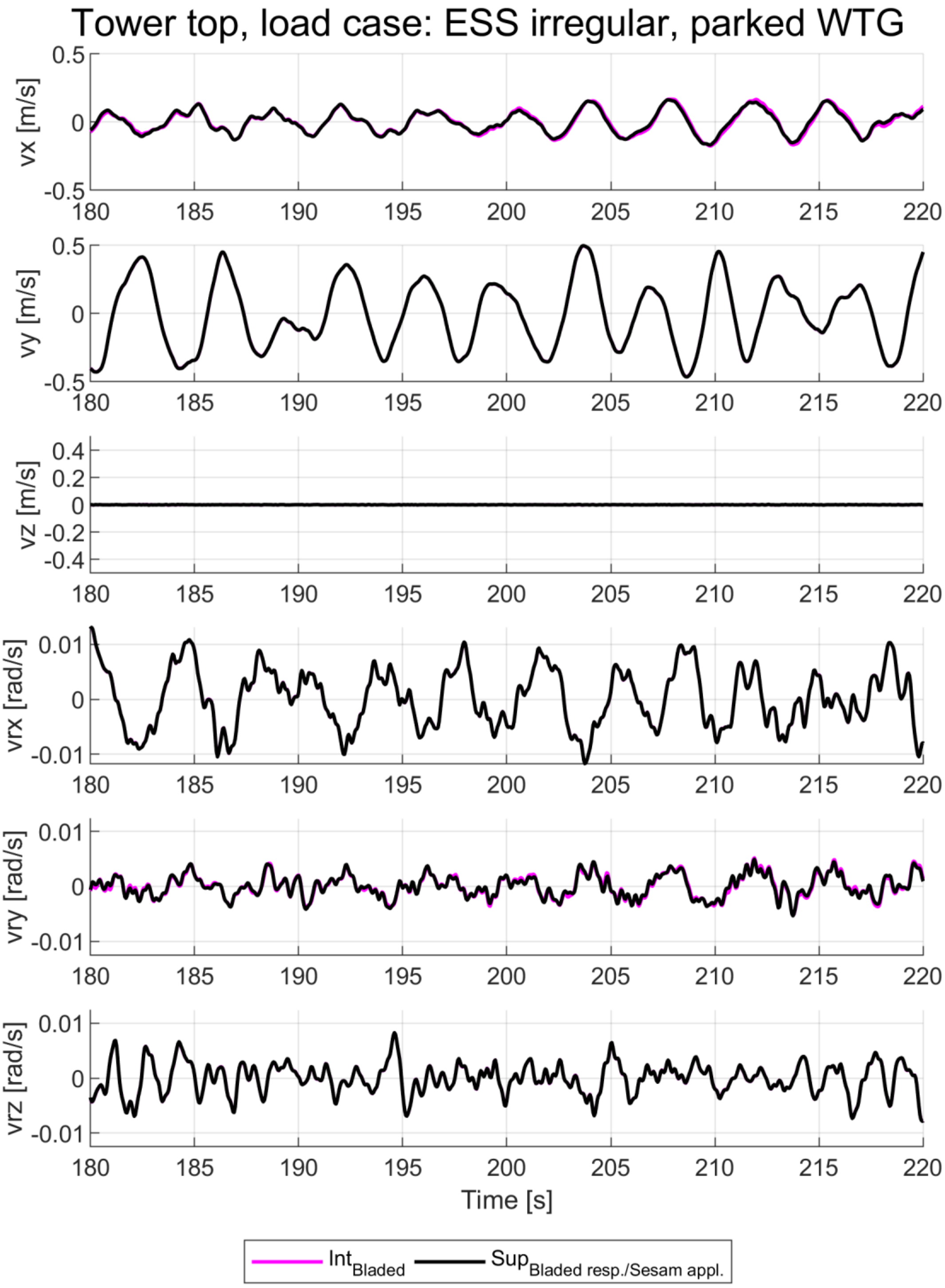


Figure 8-71 Velocities at the tower top around 200 s for the extreme load case with irregular wave.

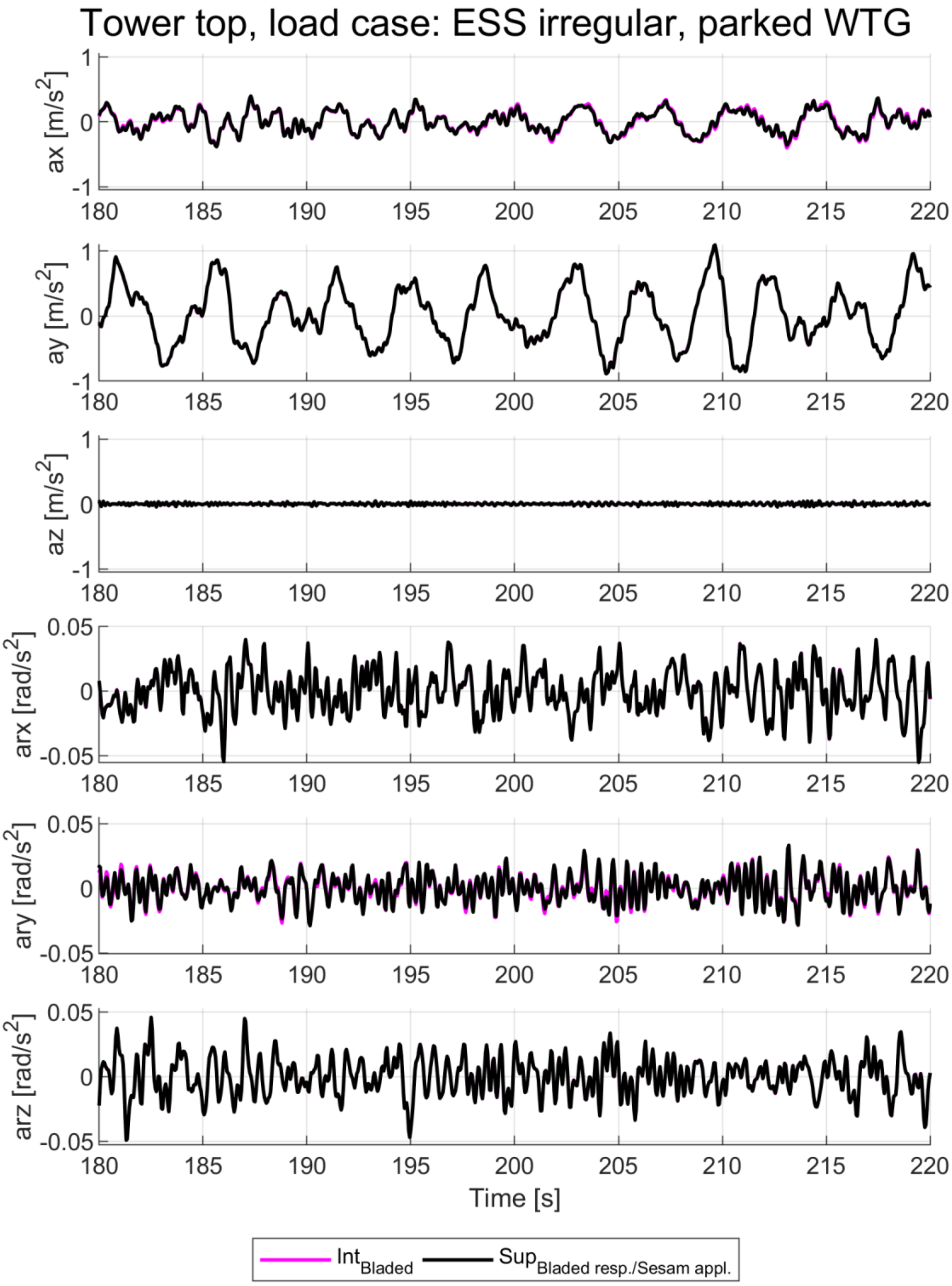


Figure 8-72 Accelerations at the tower top around 200 s for the extreme load case with irregular wave.

8.6.5.3 Regular wave

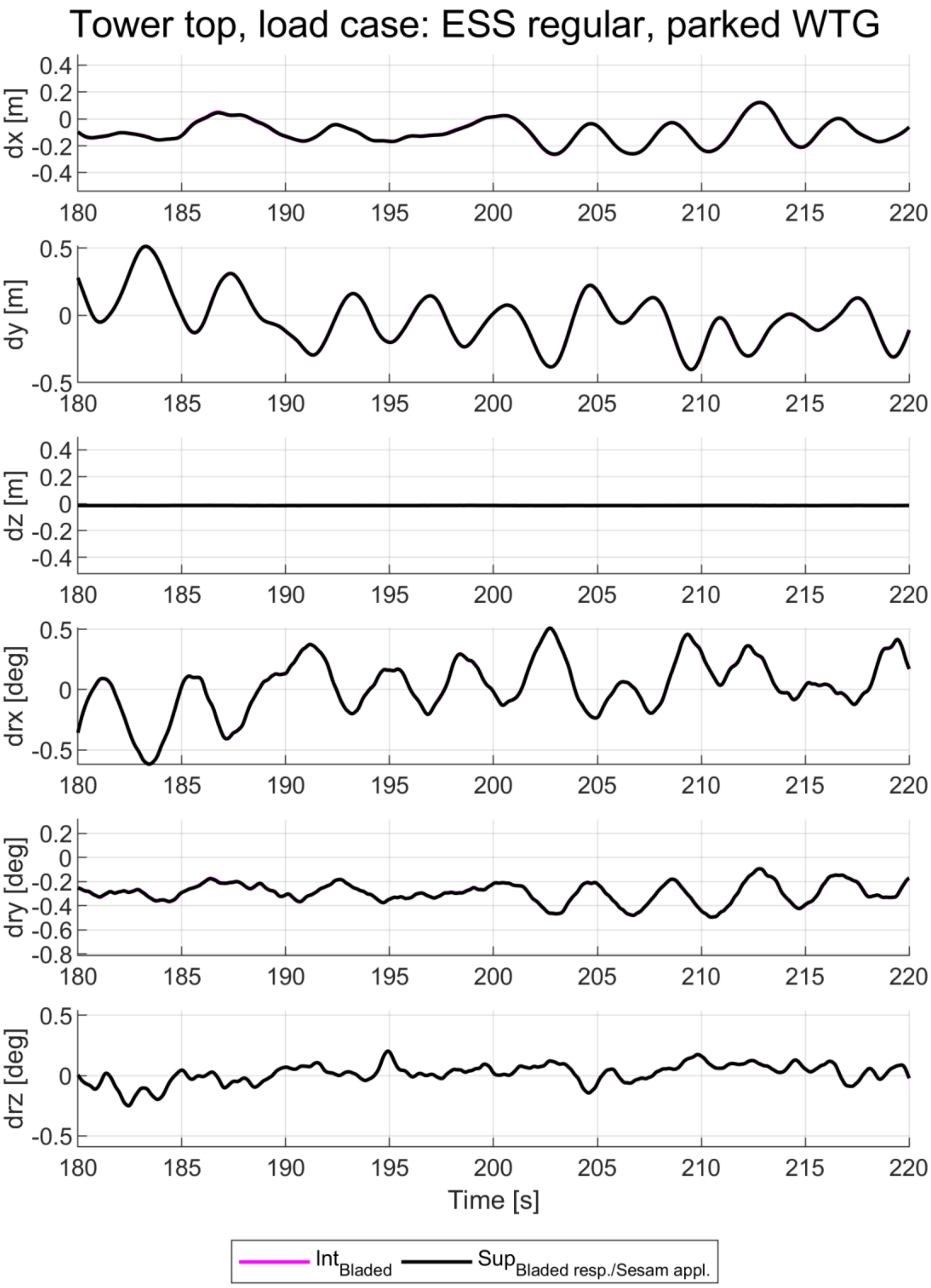


Figure 8-73 Displacements at the tower top around 200 s for the extreme load case with regular wave.

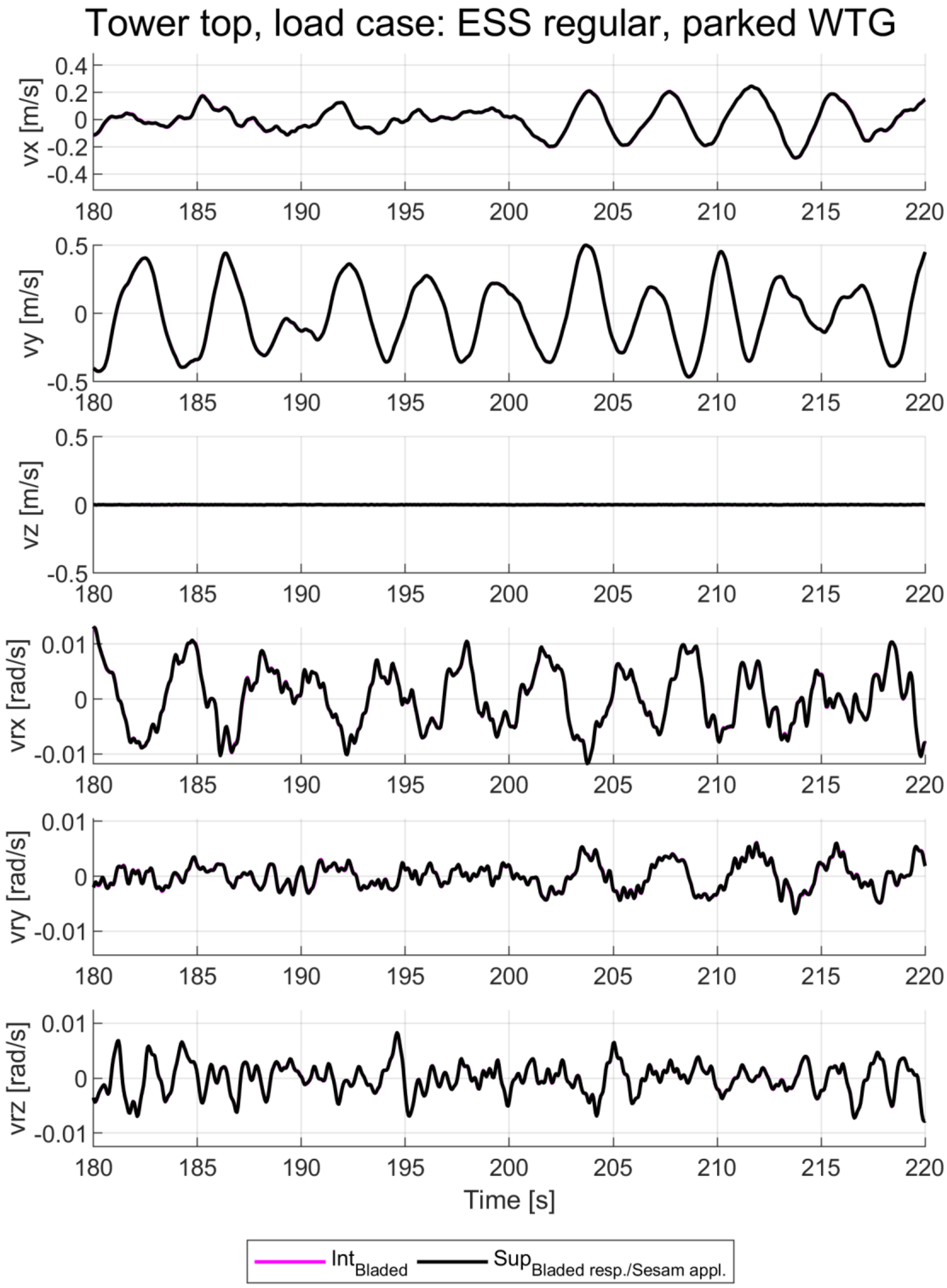


Figure 8-74 Velocities at the tower top around 200 s for the extreme load case with regular wave.

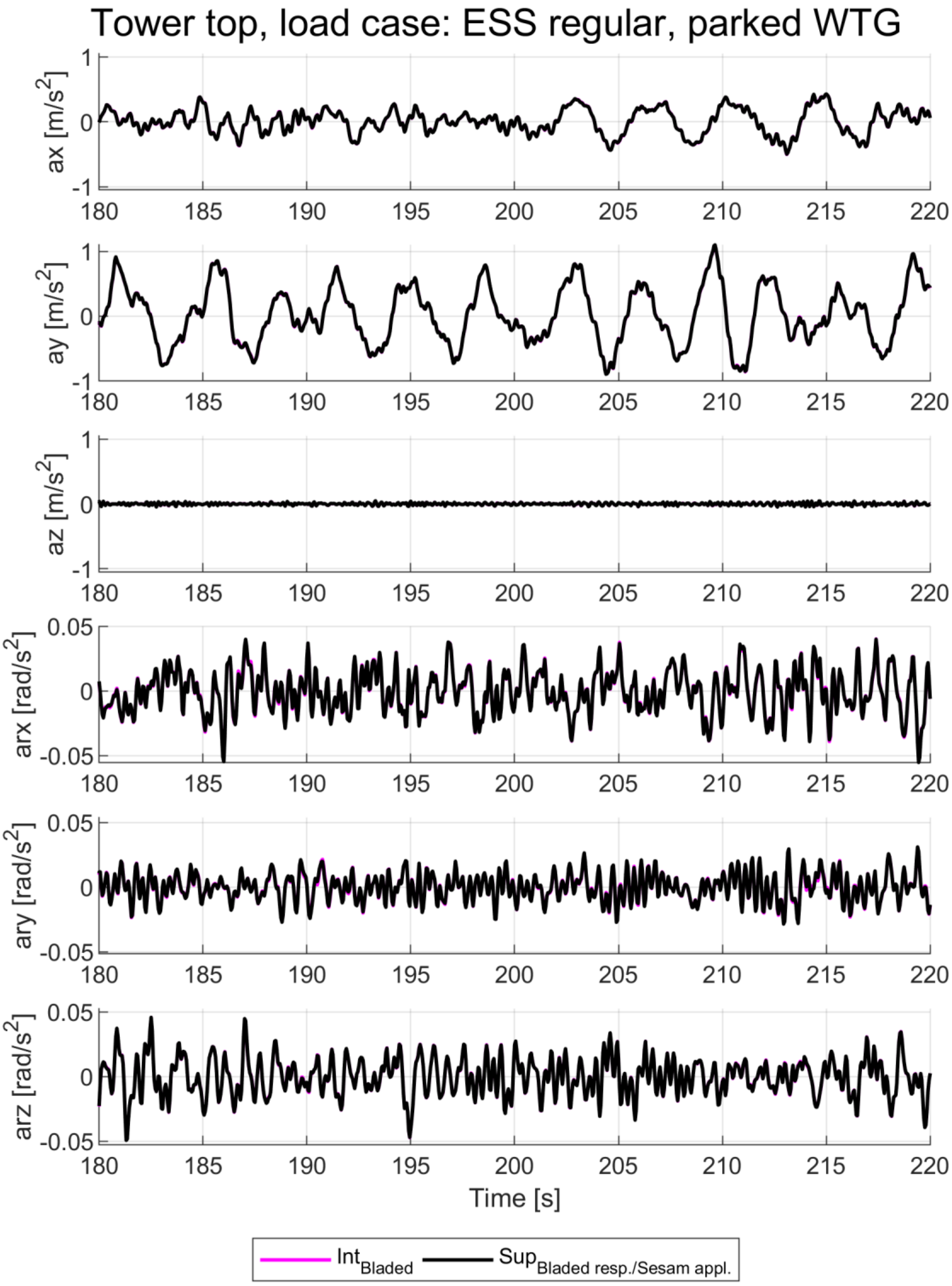


Figure 8-75 Accelerations at the tower top around 200 s for the extreme load case with regular wave.

8.7 Discussion of the results

From the previous sections 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.

For the case of wave loading only and a point mass RNA, the results of the superelement runs in Bladed and Sesam match well and closely follow the results of the Sesam integrated model regarding loads, displacements, velocities and accelerations, both at the interface, in the jacket and at the tower top. Some noticeable differences exist when comparing the results of the Bladed integrated model to the other three analyses. These differences are most likely caused by the differences in applied wave loads and different structural dynamics assumptions in Sesam and Bladed as outlined in section 6.2.

For the case including an operating wind turbine on the support structure, including wind, wave and gravity loads, the results of the superelement runs in Bladed and Sesam match well and closely follow the results of the Bladed integrated run for the fatigue load case. The same can be said for the extreme load cases. Some difference can be seen in the constrained wave cases, but that can be explained by the different wave theory that had to be used in Bladed in order to reproduce the same wave surface elevation as in Sesam.

It is worth mentioning that in order to compare the different analysis types in Sesam and Bladed properly, it was required to stay within certain bounds in both tools, as outlined in section 6.2. In a normal project, one would select a single analysis type and use that. As such, it would remove most of the limitations that were imposed to the current verification study and would allow the use of both tools to their full potential.

It is clear from the simulations that the superelement run using Sesam and Bladed gives very similar results as compared to the fully-integrated runs in Sesam and/or Bladed:

- The mode shapes and natural frequencies of the stand-alone jacket and superelement are similar.
- Combined with the RNA point mass, the modes of the system are similar.
- Combined with the wind turbine, the results of the superelement and integrated models, show that near identical responses (loads, displacements, velocities and accelerations).

Verifying the conversion process was one of the main objectives of the present verification study. In this regard, the verification study demonstrates that:

- The automatic conversions of a Sesam model into a Bladed model as well as of a Sesam model and loads into a Bladed superelement and reduced wave loads, are implemented correctly in Fatigue Manager, properly taking into account all coordinate systems and direction definitions.
- The superelement in Sesam was adequately converged before converting it into Bladed format.
- 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 .SIN result files and Sesam interface load files is implemented correctly. The generation of Sesam interface load files by Bladed is also implemented correctly.

9 GUIDING NOTES ON USING SESAM AND BLADED IN ONE WORKFLOW

Sesam and Bladed can be used in a single workflow in two different ways, the first one being an integrated approach and the second one being superelement analysis. Functionality for this exists in Sesam's Fatigue Manager and Bladed. Both processes are explained below. See also the Fatigue Manager user manual [5].

9.1 Using Sesam and Bladed for integrated design

The integrated design workflow of Sesam and Bladed is visualized in Figure 9-1. The steps are clarified as follows:

1. Create the jacket structure in GeniE and transfer the model from GeniE to Bladed. Alternatively, directly model the structure in Bladed.
2. Run all analyses in Bladed.
3. Convert the Bladed project and result files to Sesam's .SIN result file format via the converter in Fatigue Manager.
4. Set up a Fatigue Manager workspace with all desired design load cases. Add the converted .SIN result files into the design load case grid.
5. Run the Framework (FLS/ULS analysis) step.
6. Inspect the results. Optionally, redesign and re-iterate.

For more detailed guiding notes on each step, please refer to the Fatigue Manager user manual [5].

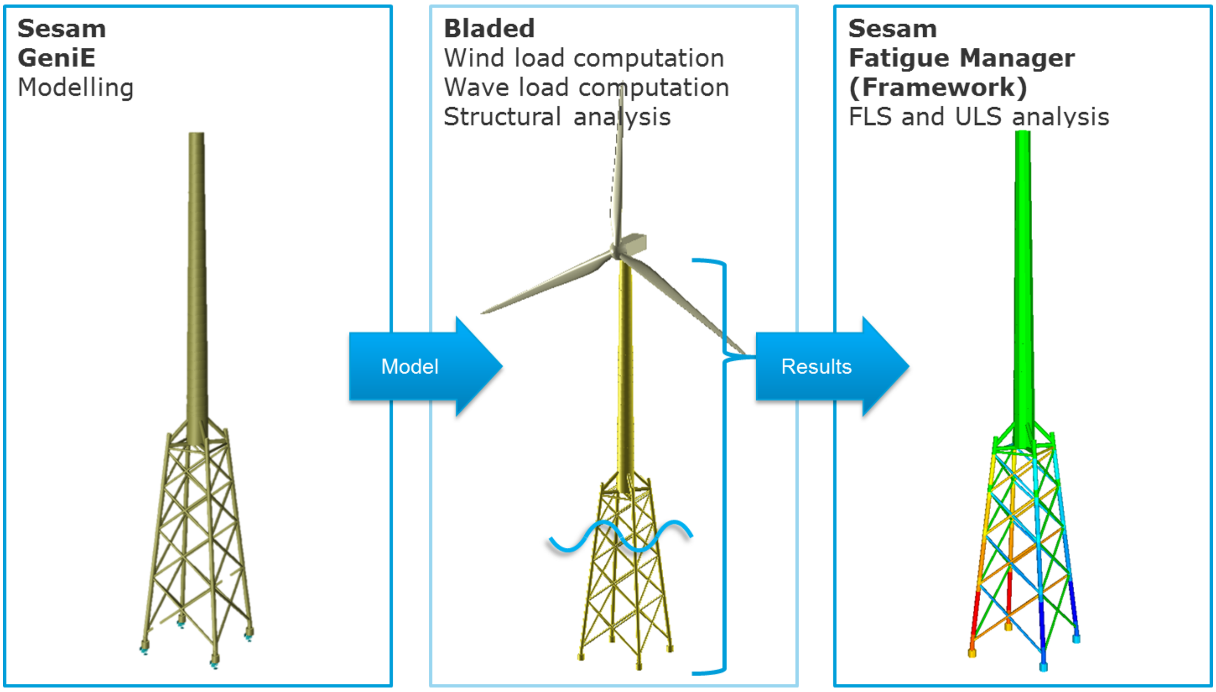


Figure 9-1: Integrated design workflow when using Sesam and Bladed

9.2 Using Sesam and Bladed for superelement analysis

The superelement analysis workflow is visualized in Figure 9-2. The steps are clarified as follows:

1. Create the jacket structure in GeniE.
2. Export the mesh of the stand-alone jacket from GeniE for use in Fatigue Manager.
3. Perform a verification study to find out how many mode shapes need to be included into the superelement.
4. Set up a Fatigue Manager workspace with all desired design load cases. No interface load files are included yet at this point.
5. Run the converter from Sesam to a Bladed superelement in Fatigue Manager. This will create a superelement data file as well as a reduced wave load file for each design load case.
6. Send the superelement and reduced wave load data files for analysis in Bladed after which interface load files are returned.
7. Add the interface load files into the design load case grid. The Autofill functionality can be used to simplify this process.
8. Run the wind, structural analysis (Sestra) and Framework (FLS/ULS analysis) steps. Note that the wave load files are the same as created during the conversion to a superelement step and can be re-used.
9. Inspect the results. Optionally, redesign and re-iterate.

For more detailed guiding notes on each step, please refer to the Fatigue Manager user manual [5].

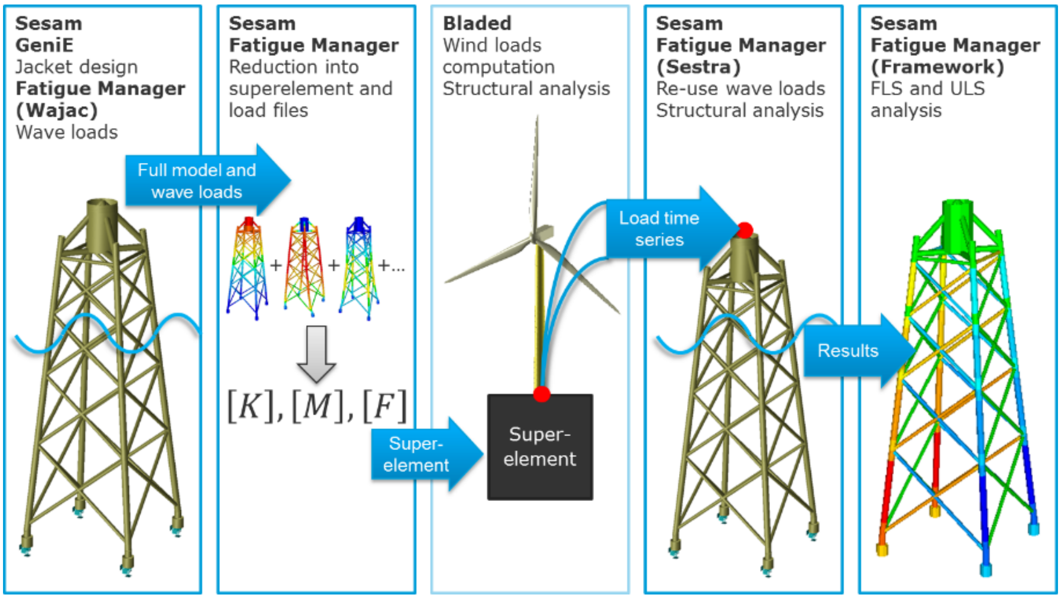


Figure 9-2: Superelement analysis workflow when using Sesam and Bladed

10 CONCLUSIONS

The purpose of the current verification study is to verify the conversion from Sesam to Bladed for integrated and superelement analysis and to verify the conversion of the results from Bladed into Sesam format.

In order to compare the results of Sesam and Bladed, their differences in modelling and analysis have been identified. Besides that, some limitations were imposed in this verification study, to match the modelling and analysis assumptions in both tools, allowing their results to be compared. Some of the differences result in assumptions and limitations for the Sesam to Bladed converter, most due to the differences in modelling functionality between Sesam and Bladed. In total, the most relevant differences are related to geometric stiffening, structural damping and wave load calculation. It should be noted that in a normal workflow one will use either Sesam or Bladed, thereby removing some of the limitations that were imposed on this comparison to match the modelling assumptions in both tools.

During the verification study it has been found that a jacket model can be properly converted from Sesam to Bladed for an integrated analysis. Besides that, it was also found that all data required for a superelement analysis, i.e. mass, damping and stiffness matrix, gravity load vector and wave load vectors, can be obtained from Sesam and outputted into the required Bladed format correctly. The superelement data is obtained from a run with gravity and calm sea only (i.e. no wave loading) while the wave loading is obtained per design load case. The coordinate systems and wind and wave direction definitions are properly taken into account.

The jacket superelement that is used in the verification study has been converged properly. This can be concluded from the spectral and spatial convergence. The spectral convergence runs show that the natural frequencies and mode shapes of the stand-alone jacket are similar for the full jacket in Sesam and for the superelement jacket, both in Sesam and Bladed. Besides that, the jacket for the Bladed integrated analysis also matches closely to the original in Sesam. The same can be said when the jacket is combined with the wind turbine tower and point mass RNA, showing similar natural frequencies and mode shapes for both analysis types in both tools.

The wave surface elevation in Sesam (which is sent to Bladed in the reduced wave load files) is the same as that used in Bladed. It should be noted that this had to be reconstructed in Bladed for the integrated analysis, since the wave load time series generators in Sesam and Bladed use different methods to generate the waves based on random seeds. The wave components used in Sesam can be exported and used in Bladed in order to get an exact match of the wave components in both tools. In a normal project, however, one would generate the wave in either Sesam or Bladed, thereby not having to go through the process of recreating the Sesam wave in Bladed.

Applying gravity and wave loads, the resulting loads and motions (displacement, velocity and acceleration) are compared at the interface, at some locations in the jacket and at the tower top. The results of the superelement runs in Bladed and Sesam match well and closely follow the results of the Sesam integrated model for all results. Some noticeable differences exist when comparing the results of the Bladed integrated model to the other three analyses for the case where the RNA is represented by a point mass. These differences are most likely caused by the differences in modelling, e.g. wave load calculation, damping, etc. in Sesam and Bladed. However, the results are comparable to those of the other three runs.

Tests were also carried out with an operating wind turbine on the support structure, including wind, wave and gravity loads. In this case, the results from the Sesam+Bladed superelement run compare well to the Bladed integrated run. This is the case for the fatigue and for the extreme load cases.

The verification study confirms that the conversions provided by Sesam to and from Bladed have been performed and implemented properly, both for the integrated model, for the superelement model and loads and for the results. The same can be said for the generation of the Sesam interface load files by Bladed. It also shows that the superelement was properly converged. This therefore allows a foundation designer to use Sesam together with Bladed in a single workflow, both for a superelement analysis as well as for an integrated design approach, with confidence in the accuracy of the conversions and results between the tools.

11 REFERENCES

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[2] W. Collier, “Superelement User Guide for Bladed,” DNV GL, Bristol, UK, 2016.

[3] W. Collier, “Report 110052-UKBR-T-37-H, Support Structure Superelement: User Guide for Bladed 4.8 and 4.9,” DNV GL, 2018.

[4] DNV GL - Digital Solutions, “Sesam User Manual - Wajac: Wave and Current Loads on Fixed Rigid Frame Structures,” DNV GL AS, Høvik, Norway, July, 2018.

[5] DNV GL - Digital Solutions, “Sesam User Manual - Fatigue Manager,” DNV GL AS, Høvik, Norway, 2019-02-07.

[6] DNV GL, “Bladed Theory Manual version 4.9,” DNV GL, Bristol, UK, 2018.

[7] R. Clough, Dynamics of Structures, second edition, McGraw Hill, 1993.

APPENDIX A
Effect of model and analysis parameters on loads and results

This appendix contains some comparisons, showing the effect of model and analysis parameters on loads and results.

A.1. Effect of geometric stiffening on free decay

This section contains information on the effect of the geometric stiffening in Bladed when comparing to a Sesam model. To compare the effects of geometric stiffening in Bladed, it is easiest to compare free decay tests in Bladed and Sesam, for the combined tower and jacket structure. The jacket and tower are modelled and a point mass RNA included.

Bladed by default includes geometric stiffening possibilities in the time domain. Sesam has the possibility to include stress stiffening, but only based on a single reference load case. To properly compare Bladed and Sesam, these effects should be disabled in both tools. When disabling stress stiffening in the Bladed integrated model, a perfect match between the Sesam and Bladed response can be seen, see Figure 1.

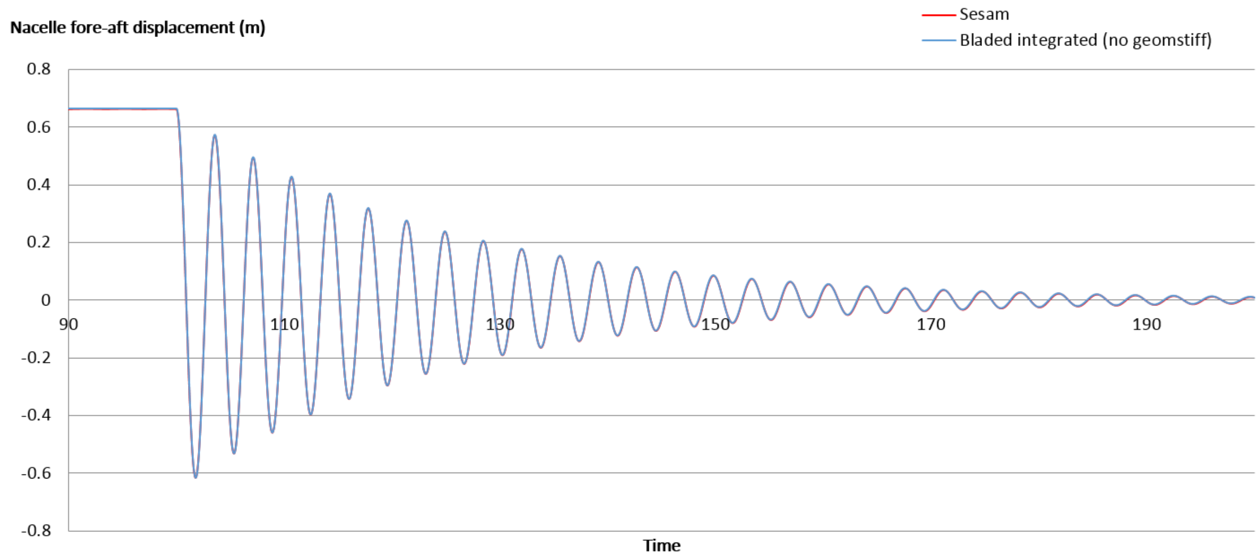

Figure 1 Free decay test comparing the integrated model in Sesam (red) and Bladed (blue) with stiffening effects disabled.

However, with stress stiffening disabled, the Bladed superelement and integrated model free decay frequencies do not match, see Figure 2. The geometric stiffening model captures some gravitational de-stiffening effect.

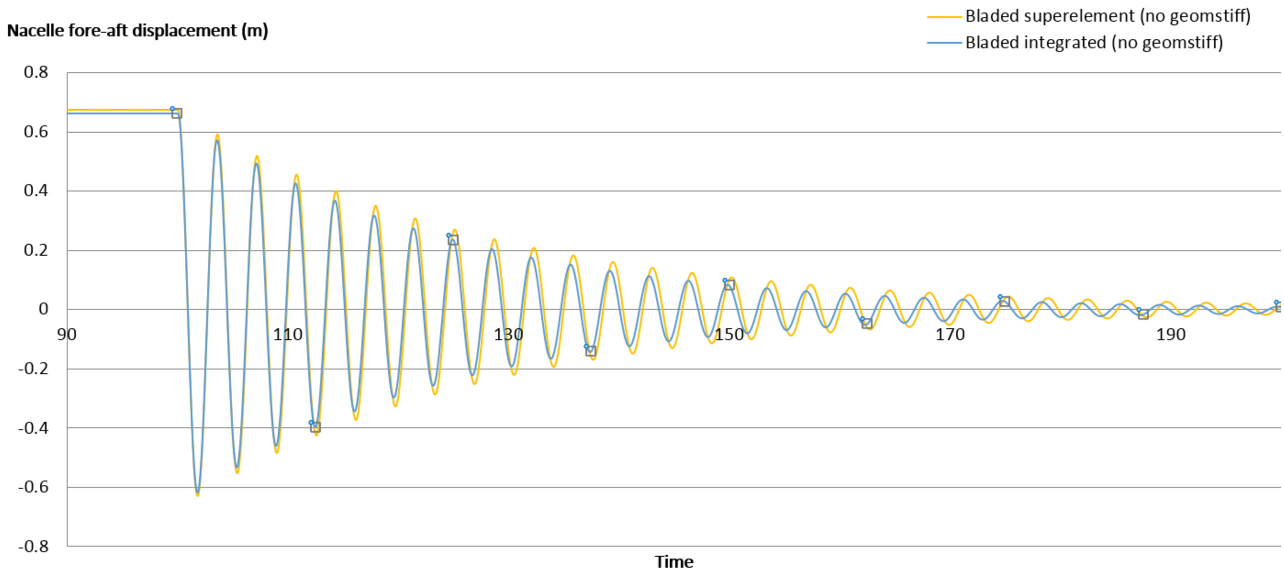

Figure 2 Free decay test comparing the integrated (blue) and superelement (yellow) model in Bladed with stiffening effects disabled.

When re-enabling the stress stiffening the Bladed superelement and integrated models match (they are in phase, but a slight tuning of damping is needed still in the image), see Figure 3.

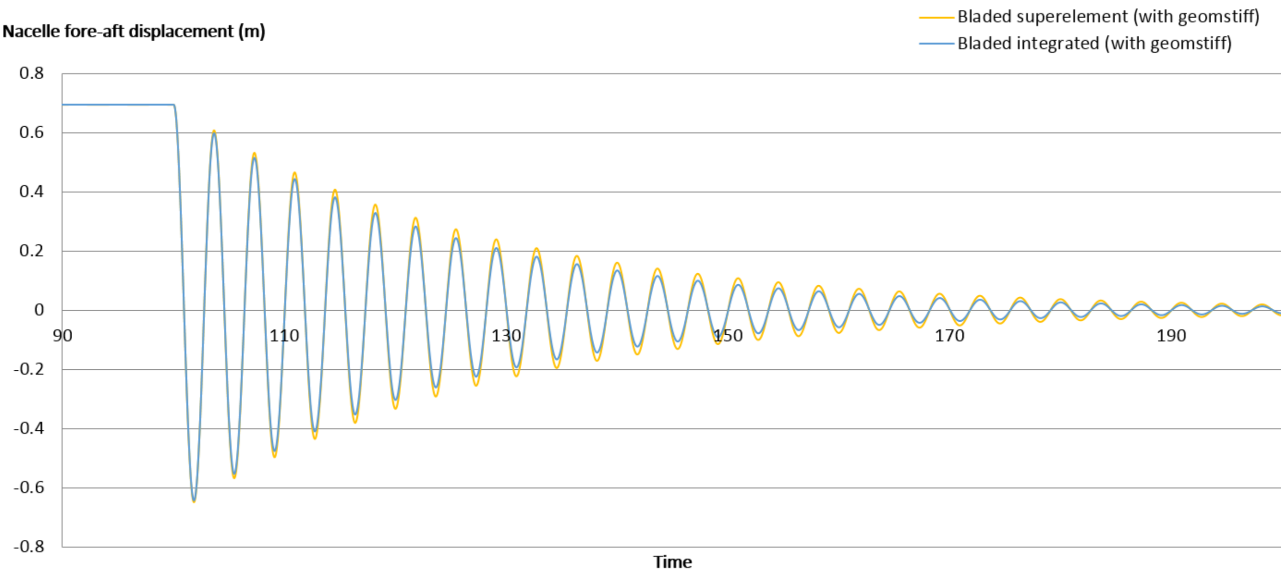

Figure 3 Free decay test comparing the integrated (blue) and superelement (yellow) model in Bladed with stiffening effects enabled.

The reason that the superelement and integrated model in Bladed only match with geometric stiffening enabled is as follows. In the superelement model, the jacket superelement is linear (and constant) while the tower is still modelled in Bladed. Because of this, the superelement and tower are modelled as two separate components in Bladed. Between each component, a multi-body node exists at which non-linear geometric effects are transferred. In this case, such a multi-body node exists at the interface between superelement and tower. Due to the tower deflection, the non-linear effects are passed into the superelement regardless of whether geometric stiffening is enabled. In the integrated model, the tower and jacket are a single component, without a multi-body node at the interface. This explains why the integrated and superelement model only give matching results with geometric stiffening enabled. Note that although this gives some effect in a free-decay test, the effect on the interface is assumed to be small. Nevertheless, passing an interface load from Bladed to Sesam including geometric stiffening effects is regarded as a benefit, thereby still applying the geometric stiffening effects onto the Sesam jacket too.

The summary of the issue could be:

- The superelement case is always slightly non-linear, as there are two structural components.
- When stress stiffening is enabled, both Bladed models capture the geometric non-linearities well. Explicitly modelling the stress stiffening in the jacket is not important as it’s so stiff.
- When stress stiffening is disabled, the Bladed integrated case is completely linear, but the Bladed superelement case is still slightly non-linear, causing some mismatch in response.

The user should be aware of the above, although it only becomes an issue when comparing free decay tests in Sesam and Bladed as above. When not performing a comparison to Sesam, it is recommended to enable geometric stiffness on the tower in Bladed.

A.2. Effect of Wheeler stretching on interface load

This section shows comparison time domain plots of the interface node bending moment in Bladed and Sesam, with and without Wheeler stretching enabled in Bladed. The wave is an irregular wave with Hs = 4.8 m and Tp = 8.6 s. The jacket and tower are modelled and a point mass RNA included.

Comparing Figure 4 and Figure 5, it is clear that disabling Wheeler stretching in Bladed significantly improves the agreement with Sesam, which did not yet include Wheeler stretching for time domain wave load calculation at the time of the verification study.

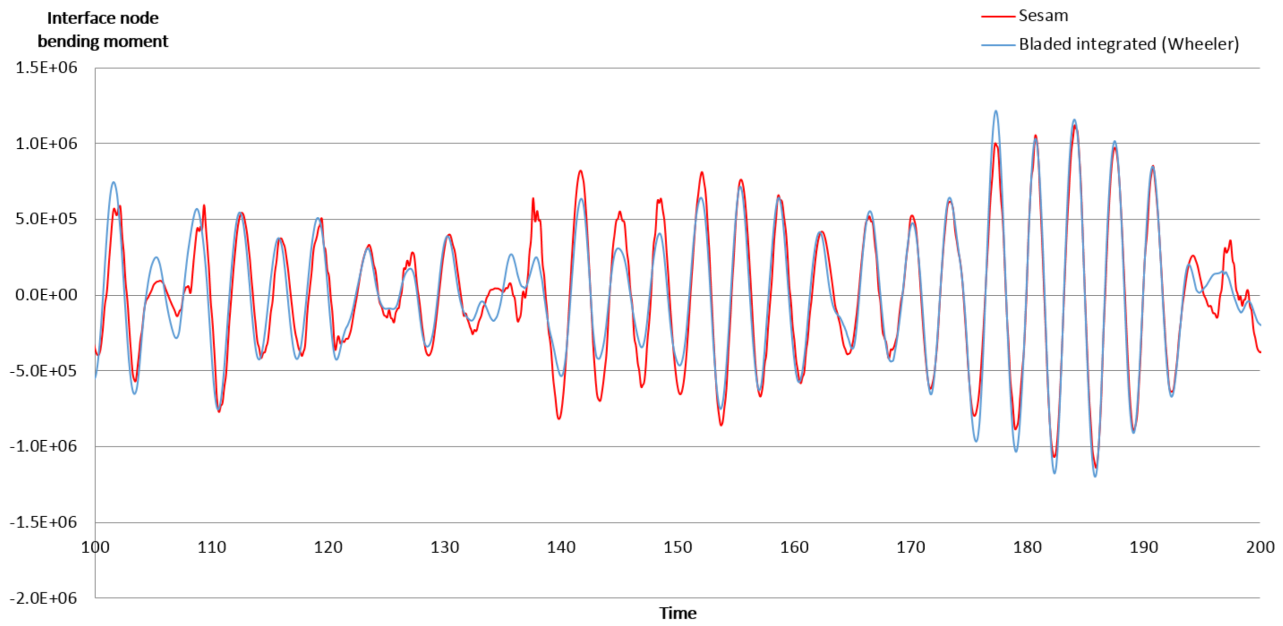

Figure 4 Superelement interface bending moment in Bladed and Sesam, with Wheeler stretching enabled in Bladed.

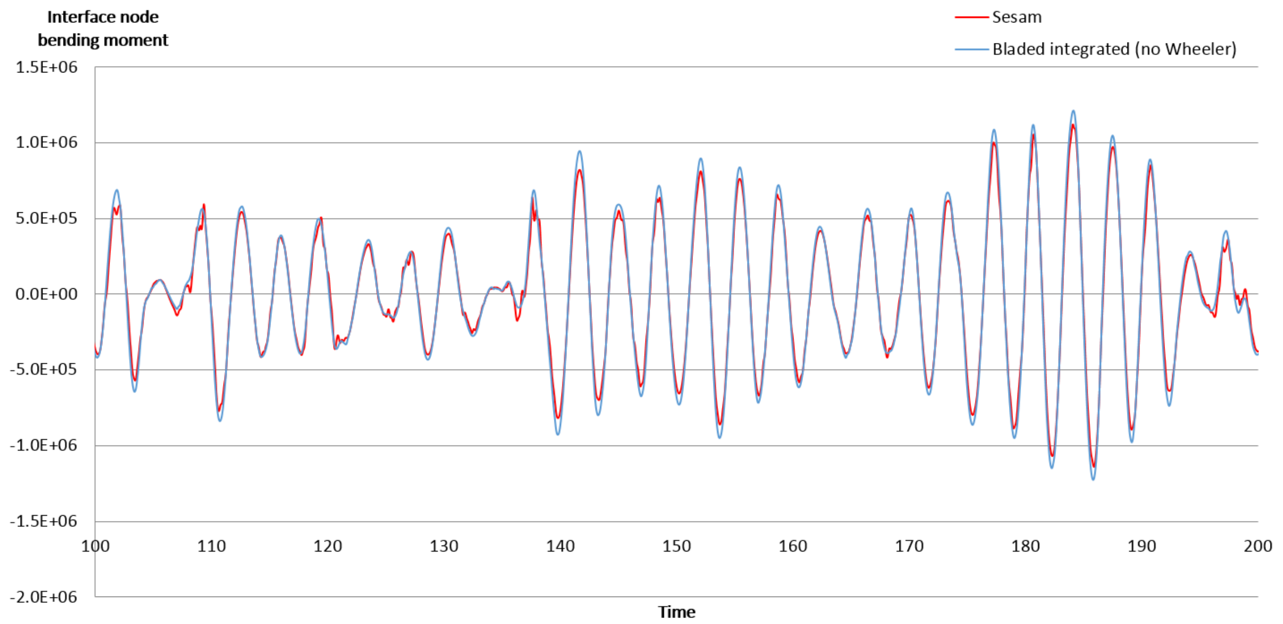

Figure 5 Superelement interface bending moment in Bladed and Sesam, with Wheeler stretching disabled in Bladed.

A.3. Effect of number of elements on wave loads

This section shows the effect on interface bending moment of doubling the number of support structure elements in Bladed. This is an attempt to address the fact the Sesam has several wave load calculation points per member, whereas Bladed only calculates wave kinematics at the member ends. The only load source is an irregular wave with Hs = 4.8 m and Tp = 8.6 s. The jacket and tower are modelled and a point mass RNA included.

In Figure 6, it is seen that the loading peaks in Bladed are reduced by doubling the number of support structure elements. This brings the load prediction closer to the Sesam interface load.

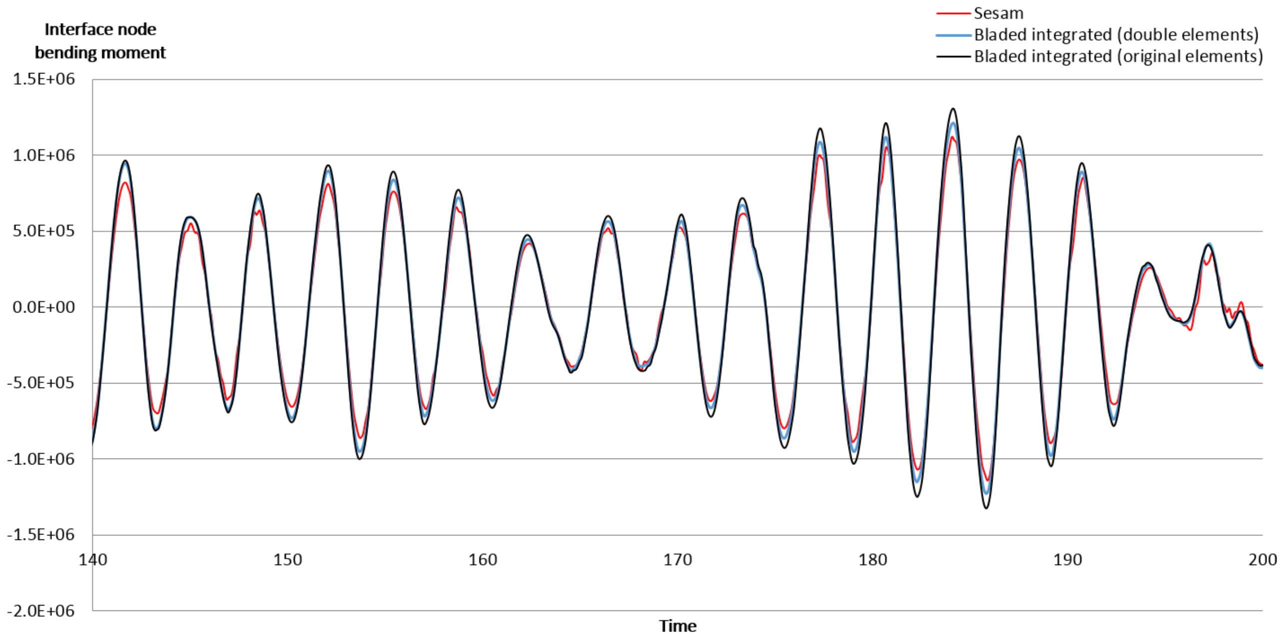

Figure 6 Effect of doubling the number of support structure elements in Bladed on interface node bending moment

APPENDIX B
Calculating Rayleigh damping for Bladed 4.8 input

In Bladed 4.8 and earlier, Rayleigh damping is not an available input. To align with damping in Sesam, and to give equivalent damping in the Bladed integrated and superelement approaches, it is desirable to define damping equivalent to Rayleigh damping in Bladed. However, Bladed 4.8 only allows modal damping as an input, so an approach is required to calculate the modal damping that is equivalent to Rayleigh damping.

In Bladed, the diagonal terms of the modal damping matrix for mode i are calculated as follows

$$C_{ii} = \frac{2\zeta_i K_{ii}}{f_i}$$

where $[C] = modal\ damping\ matrix, C_{ii}\ are\ the\ diagonal\ elements$
$[K] = modal\ stiffness\ matrix, K_{ii}\ are\ the\ diagonal\ elements$
$\zeta_i = modal\ damping\ ratio$
$f_i = modal\ frequency$

Rayleigh damping (calculated for the modal matrices) takes the form

$$[C] = a_0[K] + a_1[M]$$

where a_0 and a_1 are user defined constants

The [K] matrix is diagonal, but [M] is not. The assumption is made to ignore off-diagonal terms in [M]. We can therefore write

$$C_{ii} = a_0 K_{ii} + a_1 M_{ii}$$

To (approximately) achieve Rayleigh damping in the Bladed tower, we can enter a value of modal damping ζ_i as

$$\zeta_i = \frac{f_i\,(a_0 K_{ii} + a_1 M_{ii})}{2K_{ii}}$$

The values K_{ii} and M_{ii} can be output by Bladed 4.8 by selecting the option "Output blade and tower finite element matrices" in the *Additional Items* screen.

As an aside, it is noted that the modal frequency f_i is calculated by Bladed as

$$f_i = \sqrt{\frac{K_{ii}}{M_{ii} + M_{i,rotor}}}$$

where $M_{i,rotor}$ depends on the RNA mass and inertia, and is different for each attachment mode. For the normal "internal" modes, $M_{i,rotor}$ would be zero.

$M_{i,rotor}$ is calculated by transforming the 6x6 inertia matrix for the RNA by the mode shapes of the tower top node. So

$$M_{i,rotor} = \Psi^T\,[M_{RNA}]\,\Psi$$

where $[M_{RNA}]$ is the 6x6 RNA mass matrix
Ψ is the mode shape matrix for the tower top node only

For the "no turbine" case, the RNA mass is included in the tower itself, so $M_{i,rotor}$ is zero. This case yields a simplified expression for the damping on each mode

$$\zeta_i = \frac{\left[a_0 f_i + \frac{a_1}{f_i}\right]}{2}$$

APPENDIX C
Unified model in Bladed 4.9 for superelement and integrated damping

The integrated and superelement approaches use a different structural mode basis, as illustrated in **Error! Reference source not found.**. In an integrated model, modes cover the entire support structure, w hereas in the superelement approach, separate mode shapes are defined for the superelement and tower modes.

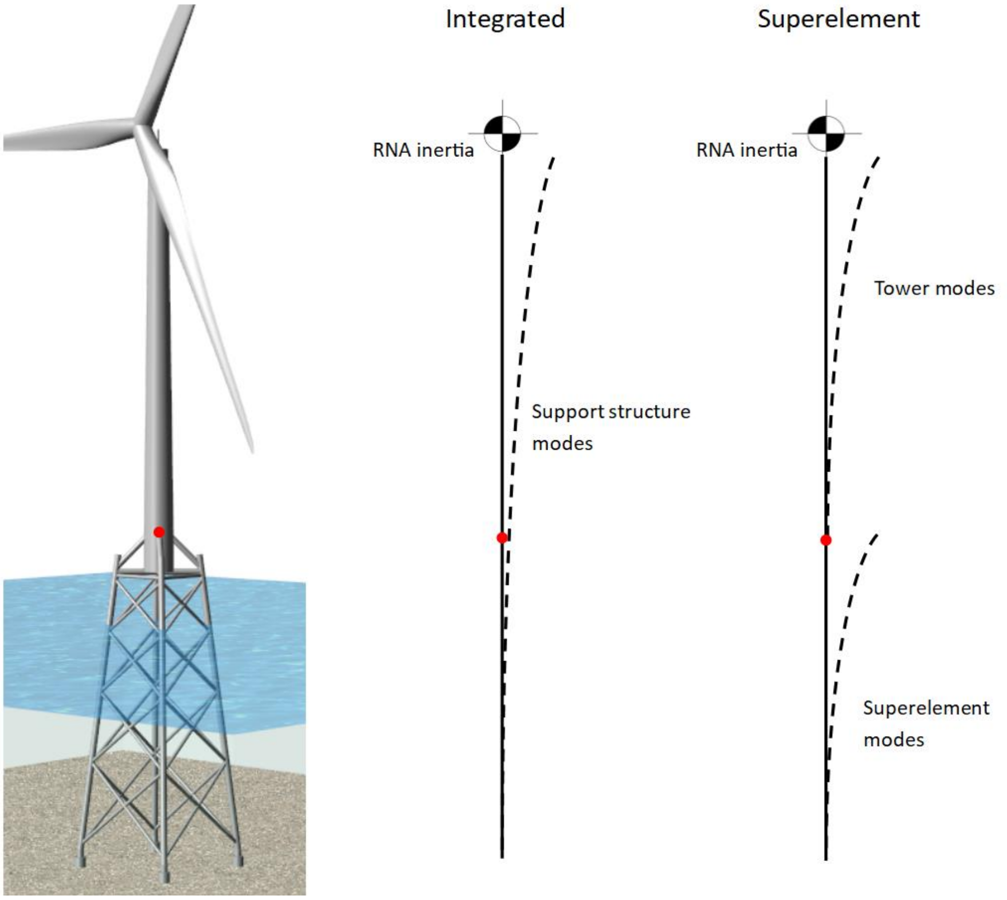

Figure 7 Modal basis in integrated and superelement approaches

In Bladed, damping is defined on the modal degrees of freedom. This leads to the question *how can equivalent damping be defined in the integrated and superelement approaches?*

In this section, the methods and challenges for damping definition are discussed for both integrated and superelement approaches. A method is then described that overcomes these difficulties and allows equivalent damping to be defined on integrated and superelement approaches.

C.1. Integrated model damping in Bladed

For an integrated model, typically modal damping ratios are defined on the uncoupled Craig Bampton vibration support structure modes.

The modes are used to calculate modal stiffness and mass matrices for the support structure. The structure of the modal mass and stiffness matrices are shown in equation (C.1). The stiffness matrix is diagonal, but the mass matrix is not.

$$[M_{SS}] = \begin{bmatrix} M_{SS11} & M_{SS12} & M_{SS13} & . \\ M_{SS21} & M_{SS22} & M_{SS23} & \\ M_{SS31} & M_{SS32} & M_{SS33} & \\ . & & & . \end{bmatrix}$$

$$[K_{SS}] = \begin{bmatrix} K_{SS11} & 0 & 0 & . \\ 0 & K_{SS22} & 0 & \\ 0 & 0 & K_{SS33} & \\ . & & & . \end{bmatrix} \qquad \text{(C.1)}$$

where subscript SS is short for support structure.

In order to calculate the frequency of each mode, the RNA inertia associated with each attachment mode must also be taken into account. For each attachment mode, a quantity $M_{i,rotor}$ is defined as follows

$$M_{i,rotor} = \Psi^T \, [M_{RNA}] \, \Psi \qquad \text{(C.2)}$$

where $[M_{RNA}]$ is the 6x6 RNA inertia matrix
Ψ is the mode shape matrix for the tower top node only

The modal angular frequency ω_i is then calculated as

$$\omega_i = \sqrt{\frac{K_{SSii}}{M_{SSii} + M_{i,rotor}}} \qquad \text{(C.3)}$$

where $M_{i,rotor}$ is non-zero for each attachment mode and zero for the normal modes.

The support structure modal damping matrix is the calculated as shown in equation (C.4).

$$[C_{SS}] = 2\begin{bmatrix} \frac{\zeta_1 K_{SS11}}{\omega_1} & & & \\ & \frac{\zeta_2 K_{SS22}}{\omega_2} & & \\ & & . & \\ & & & . \end{bmatrix} \qquad \text{(C.4)}$$

where

ζ_i are the modal damping ratios
ω_i are modal angular frequencies (rad/s)
K_{SSii} are the diagonal terms of the modal stiffness matrix

C.2. Superelement model damping (Bladed 4.8)

In Bladed 4.8, damping is defined separately on the tower and superelement, which each have their own mode shapes and damping definitions.

For the superelement, typically Rayleigh damping parameters are available for the superelement based on the superelement mass and stiffness matrices.

$$[C_{SE}] = a_0[M_{SE}] + a_1[K_{SE}] \tag{C.5}$$

The tower modal damping matrix will take a similar form to that for the integrated approach.

$$[C_T] = 2\begin{bmatrix} \frac{\zeta_1 K_{T11}}{\omega_1} & & & \\ & \frac{\zeta_2 K_{T22}}{\omega_2} & & \\ & & \cdot & \\ & & & \cdot \end{bmatrix} \tag{C.6}$$

These matrices are simply combined to give a support structure damping matrix for the following format.

$$[C_{SS}] = \begin{bmatrix} [\; C_{SE} \;] & [\; 0 \;] \\ [\; 0 \;] & [\; C_T \;] \end{bmatrix} \tag{C.7}$$

where subscript SS is short for support structure
subscript SE is short for superelement
subscript T is short for tower

There are two potential problems with this approach.

Firstly, the "cross terms" between the tower and superelement components are zero. This means that it is not possible with this approach to specify damping in a Bladed superelement model that is exactly equivalent to damping values that are specified on whole support structure modes.

Secondly, the supplied superelement damping matrix does not typically account for the effect of the inertia of the tower and rotor nacelle assembly (RNA).

C.3. Unified damping for superelement and integrated methods (Bladed 4.9+)

It is shown in section C.1 and C.2 that the described damping methods are not equivalent, for the following reasons:

1. Damping is specified on a different set of modes for the superelement and integrated approaches.

2. The superelement damping method does not include cross terms between the tower and superelement damping.

3. The superelement damping approach does not take into account the inertia of the tower and RNA when calculating the superelement damping.

To unify the damping for the superelement and integrated approaches, it is proposed to define the damping on a set of modes that is common to both approaches i.e. the coupled vibrational modes for the support structure. If the structural properties of the superelement are defined in a valid way, then the support structure coupled modes will be very similar to the integrated case.

C.3.1. Theory basis

The aim is to specify damping on the support structure coupled modes, and then transform this damping onto the actual degrees of freedom for the tower and superelement which are used in the simulation.

Consider the partitions of the system mass and stiffness matrices relating to the support structure degrees of freedom. For the superelement approach, the uncoupled support structure mass and stiffness matrices have the form shown in equation (C.8) and (C.9).

$$\left[M_{SS\,uncoupled}\right] = \begin{bmatrix} \left[\quad M_{SE} \quad\right] & \left[\quad 0 \quad\right] \\ \left[\quad 0 \quad\right] & \left[\quad M_T \quad\right] \end{bmatrix} \tag{C.8}$$

$$\left[K_{SS\,uncoupled}\right] = \begin{bmatrix} \left[\quad K_{SE} \quad\right] & \left[\quad 0 \quad\right] \\ \left[\quad 0 \quad\right] & \left[\quad K_T \quad\right] \end{bmatrix} \tag{C.9}$$

For the integrated approach, the same matrices have a more simple form, based on the form shown in equation (C.1), as shown in equations (C.10) and (C.11).

$$\left[M_{SS\,uncoupled}\right] = \left[\left[\quad M_{SS} \quad\right]\right] \tag{C.10}$$

$$\left[K_{SS\,uncoupled}\right] = \left[\left[\quad K_{SS} \quad\right]\right] \tag{C.11}$$

Note that M_{SS} and M_T include the influence of the rigid RNA inertia on each tower attachment mode. For the purpose of the damping calculation, M_{SE} is edited to include the influence of the tower and the rigid RNA on each constraint mode, using a method equivalent to the formulation in equation (C.2).

The coupled mode shapes for the support structure are found by solving the structural eigen problem using the uncoupled mode shape matrices. The number of coupled mode shapes obtained for the support structure is equal to the sum of the number of tower and superelement modes.

$$\left[K_{SS\,uncoupled}\right]\psi_i = \omega_i^2\left[M_{SS\,uncoupled}\right]\psi_i \tag{C.12}$$

where

ψ_i are the mode shape vectors
ω_i are modal angular frequencies (rad/s)

The assembled square mode shape matrix $[\Psi]$, where each column holds an individual mode shape ψ_i, describes coupled mode shapes in terms of the contributions from the uncoupled mode shapes. The mode shape matrices are used to transform uncoupled properties to coupled properties:

$$\begin{aligned} \left[K_{coupled}\right] &= \left[\Psi^T\right]\left[K_{uncoupled}\right][\Psi] \\ \left[M_{coupled}\right] &= \left[\Psi^T\right]\left[M_{uncoupled}\right][\Psi] \end{aligned} \tag{C.13}$$

Damping is specified on the coupled modes using proportional or modal damping

Proportional damping: $$[C_{coupled}] = a_0[M_{coupled}] + a_1[K_{coupled}] \tag{C.14}$$

Modal damping: $$[C_{coupled}] = 2\begin{bmatrix} \frac{\zeta_1 K_{coupled_{11}}}{\omega_1} & & \\ & \frac{\zeta_2 K_{coupled_{22}}}{\omega_2} & \\ & & \ddots \end{bmatrix} \tag{C.15}$$

where

a_0 and a_1 are proportionality constants
ζ_i are modal damping ratios
ω_i are modal angular frequencies (rad/s)

This damping on the coupled modes is then transformed back onto the uncoupled modes for use in the simulation

$$[C_{SS}] = [\Psi^T]^{-1}[C_{coupled}]\,[\Psi]^{-1} \tag{C.16}$$

C_{SS} is a full matrix that has coupling terms between the tower and superelement components (for a superelement model), or coupling between the support structure modes (for and integrated model). C_{SS} also includes the influence of the RNA inertia.

C.3.2. Results comparison

The effect of specifying damping on the support structure coupled modes is demonstrated in Figure 8.

The coupled mode damping ratios for an integrated and superelement model are compared with the RNA included. The support structure coupled mode frequencies are derived by running a Campbell diagram calculation with rigid RNA. The target damping ratio is 0.5% on the first two modes, and 1.0% on the second two modes.

The orange bars show the damping ratios when damping is defined separately on the tower and superelement modes. The grey and blue bars show the damping ratios for integrated and superelement approaches with damping defined on the support structure coupled modes. It is seen that defining the damping on support structure coupled modes results in equivalent damping for the two approaches up to 5Hz. Good agreement was also observed at higher frequencies, although this is not presented in the figure.

Definition of damping on the uncoupled superelement and tower modes results in incorrect damping on the first two modes. If desired, manual tuning can be carried out to give the desired damping ratio for the first few coupled modes.

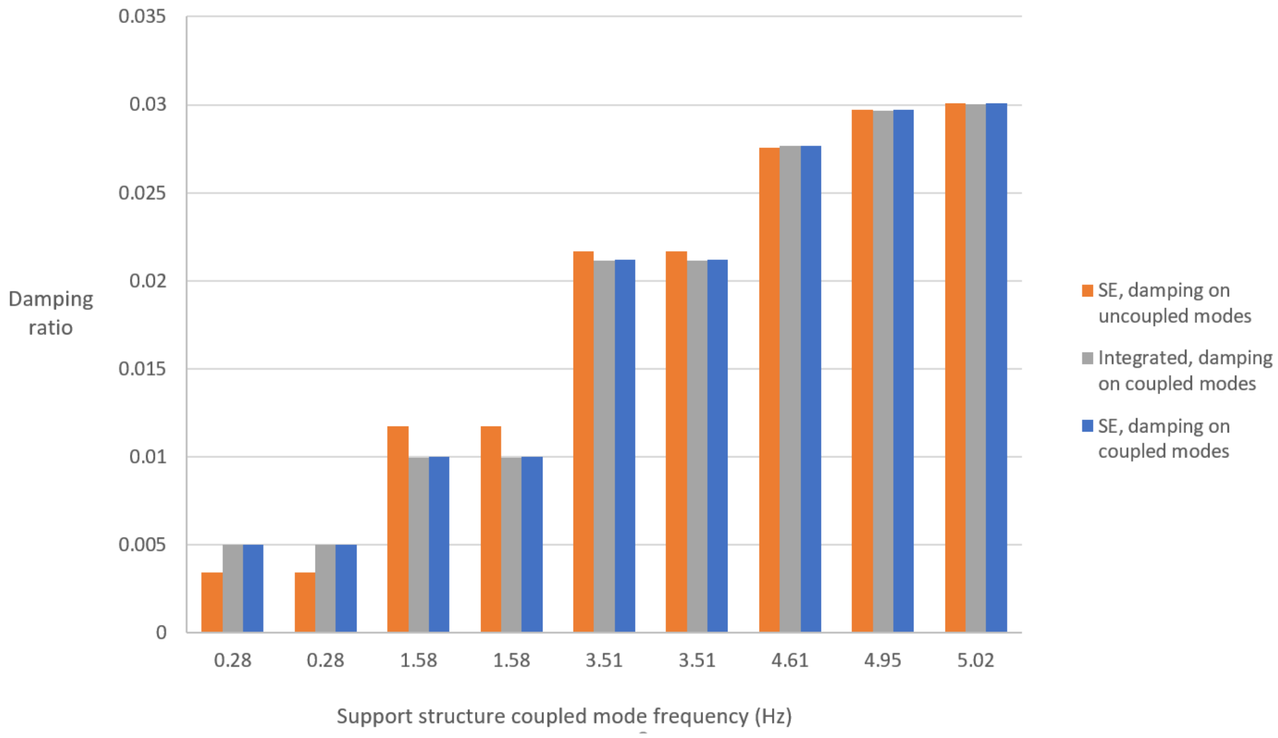

Figure 8 Support structure coupled mode damping ratios for integrated and superelement models, including effect of specifying damping on the support structure coupled modes

APPENDIX D

Generating a .SEA file for Bladed based on Sesam wave components

Sesam's Wajac is able to output the wave components it uses for its irregular wave generation using the FCOMP command. These can subsequently be read in by Bladed, so that the exact same wave surface elevation and kinematics can be reproduced.

In both Sesam and Bladed, the irregular wave is made up of linear Airy wave components. However, the implementation differs in a few ways, requiring a conversion of Wajac's wave components into Bladed.

The Airy wave formulation in Sesam's Wajac is as follows [4]:

$$\eta_{Sesam}(t) = A_n \cdot cos(\boldsymbol{k_n} \cdot \boldsymbol{X} - \omega_n \cdot t + \varphi_n)$$

where:

- η_{Sesam} = surface elevation in Sesam [m]
- A = wave component amplitude [m]
- $\boldsymbol{k}$ = two-dimensional wave number [-]
- $\boldsymbol{X}$ = horizontal coordinate vector in the global (X; Y; Z) frame of reference [m]
- ω = angular frequency [rad/s]
- t = time [s]
- φ = phase angle [rad]
- θ = wave heading [rad]
- n = harmonic wave component id [-]

The Airy wave formulation in Bladed is as follows (see section 8.9 in [6]):

$$\eta_{Bladed}(t) = A_n \cdot cos\big(k_n \cdot \big(x \cdot cos(\theta_n) + y \cdot sin(\theta_n)\big) + \omega_n \cdot t + \varphi_n\big)$$

where:

- η_{Bladed} = surface elevation in Bladed [m]
- A = wave component amplitude [m]
- k = wave number [-]
- x = distance along x-axis [m]
- y = distance along y-axis [m]
- θ = wave heading [rad]
- ω = angular frequency [rad/s]
- t = time [s]
- φ = phase angle [rad]
- n = harmonic wave component id [-]

Besides the difference in notation for the directional influence, the main difference between the formulations in Sesam and Bladed is the sign of the angular frequency component. This means that in order to use the Sesam wave components in Bladed, the conversion needs to account for this sign change. Since negative angular frequencies are not accepted as input by Bladed, the sign of the wave number and of the phase angle are changed instead.

Using the Sesam wave component data, a Bladed .SEA file can be generated. The .SEA file contains four columns. The columns and their corresponding conversion from Sesam to Bladed values are as follows:

1. Frequency: $\omega_{n,Bladed} = \frac{\omega_{n,Sesam}}{2\pi}$
2. Amplitude: $a_{n,Bladed} = a_{n,Sesam}$
3. Direction: $\theta_{n,Bladed} = 360 - \theta_{n,Sesam}$
4. Phase: $\varphi_{n,Bladed} = -\varphi_{n,Sesam}$

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