IMPLEMENTING AN INTERFACE BETWEEN BLADED AND ROSAP

Verification report of Bladed’s ROSAP interface

DNV GL in cooperation with Ramboll Offshore Wind

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1 EXECUTIVE SUMMARY

In this document a verification study is presented for the interfaces to transfer a support structure superelement between DNV GL's wind turbine design software Bladed and Ramboll's Offshore Structural Analysis Package (ROSAP) [2].

In this study, a 4-legged jacket structure is defined in ROSA and a superelement model is derived according to the Craig-Bampton method [4]. The superelement convergence is checked to ensure that the response is similar to the original jacket model in ROSA. Reduced wave loads are also derived for an irregular sea state including an extreme non-linear stream function for representing the maximum wave. The superelement is imported into Bladed, where a generic 7 MW wind turbine model is also defined. A 10-minute coupled aero-elastic simulation of the wind turbine with the superelement support structure is carried out in Bladed. The interface loads are output from the Bladed simulation and applied in ROSA to the original jacket model along with the wave loads to check that the response in ROSA is equivalent to that in Bladed.

A good match in natural frequencies is found for the original ROSA jacket model and the ROSA superelement model; the first 12 frequencies are within 0.05%. The spatial convergence at the interface node is also found to be satisfactory. Transferring the superelement from ROSA to Bladed introduces no significant errors; an almost perfect match is seen between the frequencies for the superelement jacket in Bladed and ROSA.

The interface node kinematics from the Bladed simulation and ROSA re-creation run is compared. An excellent correspondence is found in the time histories and spectra for the interface displacements and velocities. The accelerations are also reasonably similar, although some components show greater high frequency response in ROSA.

2 INTRODUCTION

2.1 General

The present verification report is written in collaboration between DNV GL and Ramboll and serves as a documentation of the interface between Ramboll's Offshore Structural Analysis Programme (ROSAP) and DNVGL's aero-elastic wind turbine design code (Bladed).

The program package ROSAP consists of various program modules, of which ROSA is the main program. ROSA is a general-purpose beam element program for static or dynamic analysis of spatial frames, truss structures and piping systems subjected to various kinds of loads including gravity, acceleration, transport, temperature, pressure, buoyancy, wave, current, wind, earthquakes and ice. Complex parts may be represented by superelements from detailed 3D shell or solid FE-models. Further capabilities include non-linear pile-soil interaction, local joint flexibility and enhanced wave kinematics with flow-dependent non-constant hydrodynamic coefficients including MacCamy-Fuchs correction etc. Besides ROSA, the program package consists of various post-processing modules for member and joint code check, deterministic, spectral and transient fatigue check, model and result visualisation and plotting etc.

Bladed is the industry standard software package for onshore and offshore wind turbine design. Bladed performs coupled analysis of the wind turbine and support structure, capturing the interactions of aerodynamic loading, hydrodynamic loading, and control system actions.

2.2 Objective

The objective of this report is to document a verification study of the interface for exchanging reduced structural models, also known as superelements, between Bladed and ROSAP.

It is demonstrated that a superelement representation of a detailed jacket foundation from ROSA can be imported into Bladed and coupled to a representative Wind Turbine Generator (WTG) model for aero-elastic load calculations. Furthermore, it is shown that interface forces extracted from the integrated simulation model in Bladed correctly recover the response at the interface, as well as selected key locations in the jacket structure, when applied on the full (non-reduced) foundation model in ROSA.

3 VERIFICATION SETUP

3.1 Approach

The commonly used approach for load calculations where the foundation is represented in the aero-elastic model in terms of a superelement is applied here, see [6] for further details. The procedure is illustrated in Figure 1 and can be summarised in the following four steps:

1. A detailed FE-model of a jacket foundation is generated in Ramboll's in-house program ROSA, along with a representative loading time series including gravity and hydrodynamic forces due to buoyancy, waves and currents.
2. The foundation model is converted into a Bladed compatible superelement with the associated reduced load time series.
3. The jacket superelement is imported into Bladed and coupled with a representative WTG model and used in an aero-elastic load calculation including the reduced load time series.
4. Internal forces are extracted at the interface between the Bladed and the ROSA models and applied to the jacket model in ROSA, in a dynamic time integration analysis.

The results at the interface node (generalized displacements, velocities and accelerations), as well as selected internal nodes at key locations in the structures from ROSA and Bladed respectively, are compared.

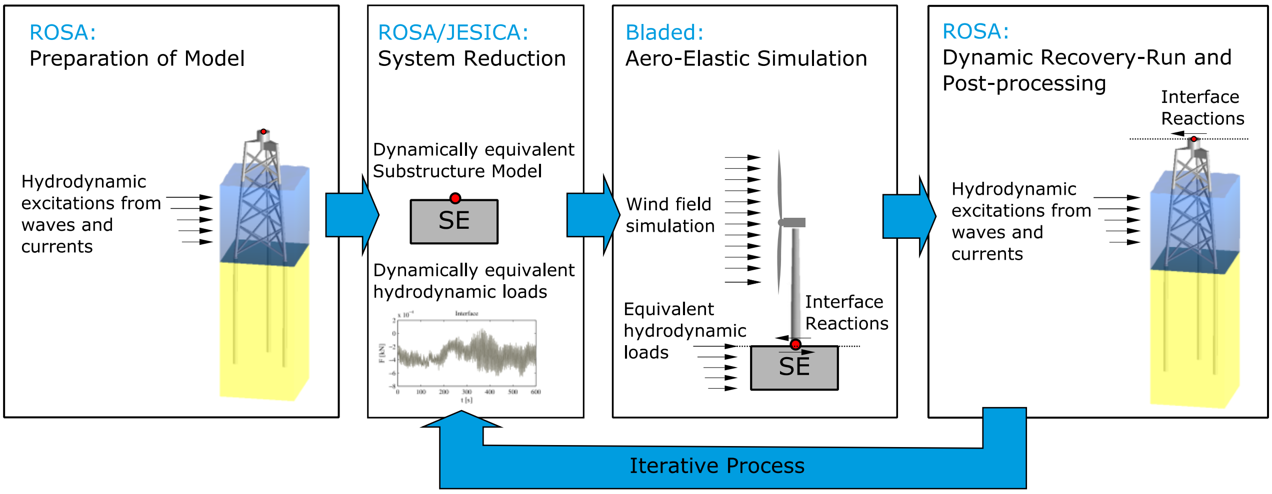

Figure 1: Superelement analysis workflow between ROSA and Bladed.

3.2 Jacket model

For verification of the ROSA-Bladed interface, a 4-legged pre-piles jacket structure with three X-braces is considered. The structure is oriented as illustrated in Figure 2. The z-axis (blue) points upwards, the x-axis (red) points North and the y-axis (green) points West. The reference level is chosen as the Lowest Astronomical Tide (LAT).

The interface is located at +20 mLAT. The legs are assumed flooded, while the braces are modelled as non-flooded.

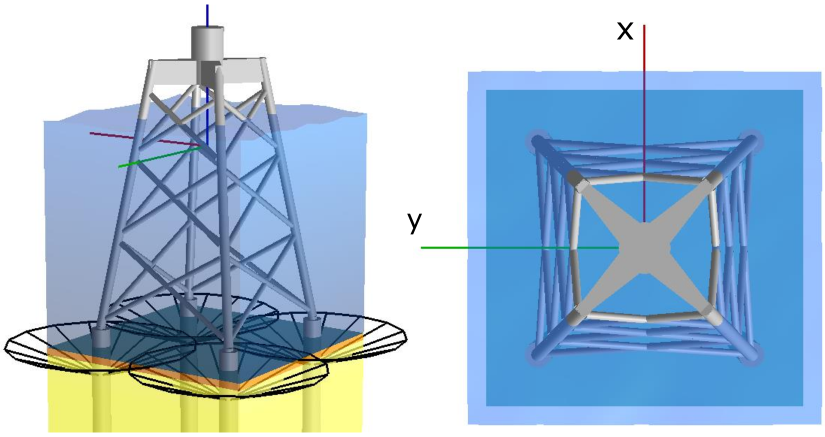

Figure 2: 4-legged jacket structure used for verification study.

3.3 Environmental conditions

The mudline is located at -33.72 mLAT, while the water level is +2.00 mLAT.

The wave load on the structure is modelled according to Morison's equation with time dependent wave kinematics represented via a JONSWAP-spectrum with governing parameters H_s = 7.50 m and T_p = 12.80 s. In order to represent an extreme sea state, it is ensured that the spectrum include a wave with maximum wave height parameters H_{max} = 13.60 m and T_{max} = 13.50 s. The parameters are summarized in Table 1.

Table 1: Wave parameters.

Sign. wave height H_s [m]	Peak wave period T_p [s]	Max wave height H_{max} [m]	Max wave period T_{max} [s]
7.50	12.80	13.60	13.50

Additionally, a depth averaged current speed of 0.8 m/s is included.

Free surface elevation time series are generated by discretising the wave spectrum. The spectrum is discretised into a number of harmonic components with a constant frequency interval Δf, and converted into the time domain via the Fast Fourier Transform (FTT) technique. For each discrete frequency, the corresponding harmonic wave amplitude is determined. To simulate an irregular sea surface, each harmonic component is assigned a random phase. The length of the part of the generated time series used in the analysis is 800 s including 200 s of start-up time. The time step used for generation of the hydrodynamic loads is 0.1 s, while a time step of 0.02 s is used in the dynamic time integration procedure to ensure a sufficient discretisation for the Generalized-alpha method [8].

The wave kinematics for the irregular waves are calculated in accordance with linear wave theory in the time domain analysis. However, the maximum irregular wave in the time series is replaced by "blending in" a corresponding non-linear wave according to the Stream function theory. This principle is illustrated in Figure 3 . The wave time series are generated such that the maximum wave occurs in the middle of the 600 s time interval after the start-up time, i.e. at t = 500 s.

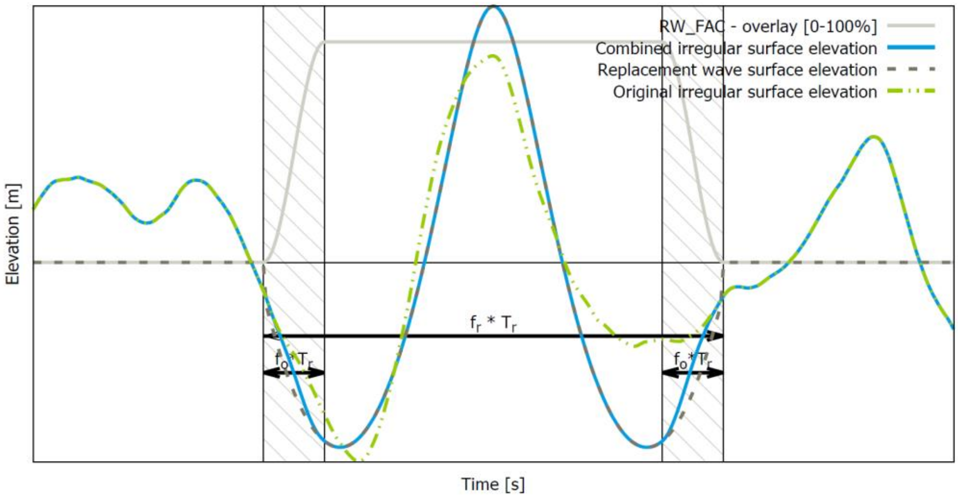

Figure 3: Principle for replacing maximum wave.

3.4 Aero-elastic model

An aero-elastic model of a generic 7MW turbine and tower was defined in Bladed, as shown in Figure 4. The tower height was 102m and the rotor diameter 155m. The superelement interface node was defined at the base of the tower, illustrated in red.

Time domain power production simulations were carried out in Bladed, using the superelement support structure generated in ROSA. A turbulent wind field was defined with a 20m/s mean speed and direction coming from North.

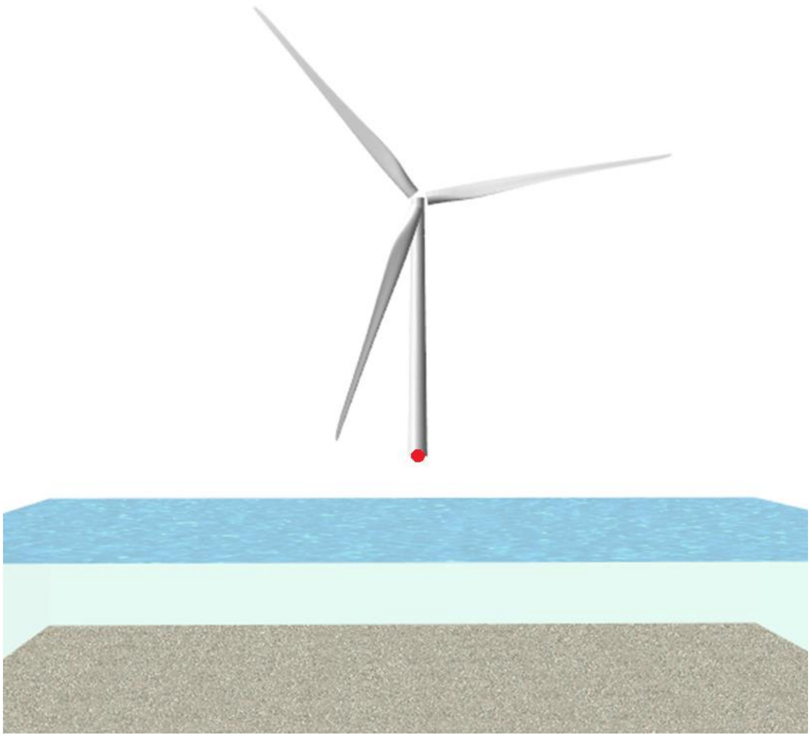

Figure 4: Generic 7MW wind turbine with superelement foundation in Bladed.

3.5 Coordinate systems

The jacket structure has been defined in the ROSA coordinate system as presented in Figure 2. This is different from the global coordinate system in Bladed where the positive x-axis points towards the South, the Y-axis points towards the East and the z-axis is directed upward as illustrated in Figure 5(b).

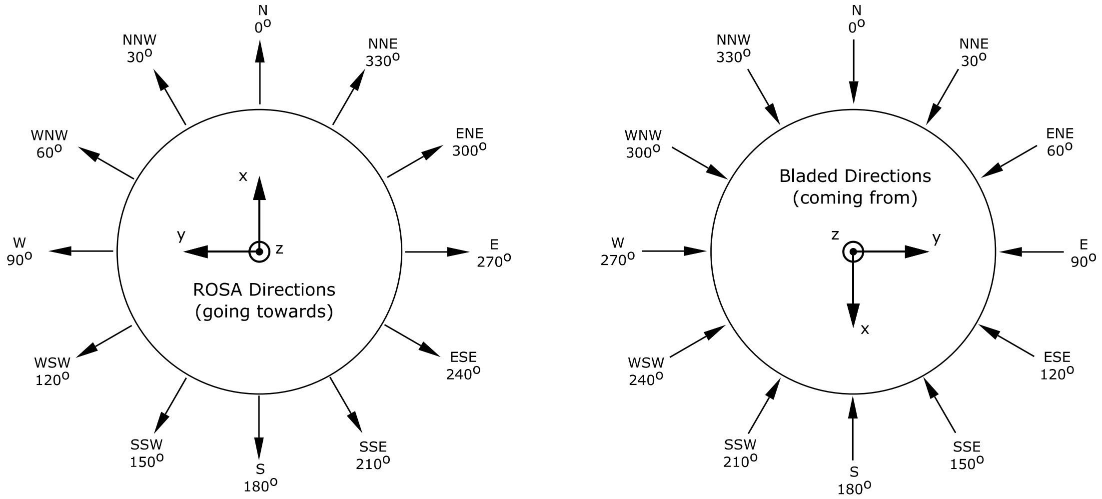

Figure 5: (a) Global coordinate system in ROSA. (b) Global coordinate system in Bladed.

The difference amounts to a plane rotation of 180° around the common global z-axes which can be achieved by a transformation of the form

$$\mathbf{x}_{ROSA} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{ROSA} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{Bladed} = \mathbf{R}\,\mathbf{x}_{Bladed}$$

which identifies the transformation matrix $\mathbf{R}$, as

$$\mathbf{R} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The following conventions for environmental data have been adopted here:

- Wind – 0° N means wind from North
- Waves – 0° N means waves from North
- Current – 0° N means current flow towards North

Based on the environmental direction, the orientation of the ROSA coordinate system will appear as for waves (and wind) with the directions shown in Figure 5. The current direction is given counter-clockwise relative to the wave direction, i.e. direction 0 means that the current is in the same direction as the waves.

3.6 Software versions

The following ROSA and Bladed versions have been used:

- ROSA 5.1
- WAVGEN 5.1
- JESICA 5.1

  Bladed 4.8.0.71

4 SUPERELEMENT FORMAT FOR BLADED

The superelements from ROSA are stored in a binary SEB-format. This may be converted into a Bladed compatible ASCII-format via a specially developed converter – *Sebreader.exe*[1]. This can be run in batch/prompt mode via the syntax:

```
Sebreader.exe input1 input2 input3 input4
```

where

- `input1` is the filename of the SEB-file to be converted.
- `input2` is the filename of the generated ASCII-output file. If 0 the input filename is used.
- `input3` is the filename of a txt-file holding the transformation matrix associated with the transformation between the ROSA and Bladed coordinate systems. The content of the txt file should be:

```
-1   0   0   0   0   0
 0  -1   0   0   0   0
 0   0   1   0   0   0
 0   0   0  -1   0   0
 0   0   0   0  -1   0
 0   0   0   0   0   1
```

  in accordance with the transformation described in section 3.5.
- `input4` is an optional output flag. If equal to 1, three ASCII-files will be generated with endings SMAT, WLVEC and ses/ASCIIDAT as described in the following section.

4.1 Superelement and wave load files for Bladed

The mass, stiffness and damping matrices, along with the gravity vector are contained in the ASCII-file with file ending .SMAT, following the format specified in [5]. The damping matrix is explicitly included here, based on the Rayleigh damping approach. This could alternatively be obtained by a linear combination of the stiffness and mass matrices if another target damping is needed. An example of the format is illustrated in Figure 6.

[1] The SEB-converter can be provided by Ramboll upon request.

```
1      36 ULS_SE_3X4L_0001_ro
1 Mass
 9.74771405E+005 -8.7185222E+001 2.72117766E+002 -8.0857075E+002 -7.5760750E+006 2.14234110E+004 7.14639963E+002 -1.2064380E+002 -2.9580899E+001 3.23332598E-002
 -8.7185222E+001 9.74763466E+005 5.33976314E+002 7.57596241E+006 -7.2073414E+002 -9.9516789E+003 -1.2058602E+002 -7.1526534E+002 1.96087156E+000 -6.0960889E-001
 2.72117766E+002 5.33976314E+002 5.04428219E+005 -1.0379241E+001 -6.2051289E+001 5.14326789E+003 -7.4718938E-002 -1.3213658E-001 6.17751181E-001 6.75836334E-004
 -8.0857075E+002 7.57596241E+006 -1.0379241E+001 6.37833592E+007 1.53162824E+003 -7.6977530E+004 -1.1170634E+003 -6.6044566E+003 1.94904727E+001 -5.9363743E+000
 -7.5760750E+006 -7.2073414E+002 -6.2051289E+001 1.53162824E+003 6.37847010E+007 -1.9957171E+005 -6.5988322E+003 1.11703026E+003 2.72998314E+002 -1.3422938E-001
 2.14234110E+004 -9.9516789E+003 5.14326789E+003 -7.6977530E+004 -1.9957171E+005 4.67266775E+007 3.07985956E+002 -2.3337907E+001 6.65311589E+003 1.71416570E+000
 7.14639963E+002 -1.2058602E+002 -7.4718938E-002 -1.1170634E+003 -6.5988322E+003 3.07985956E+002 1.00000000E+000 1.10099037E-016 7.48207919E-016 1.67305948E-017
 -1.2064380E+002 -7.1526534E+002 -1.3213658E-001 -6.6044566E+003 1.11703026E+003 -2.3337907E+001 1.10099037E-016 1.00000000E+000 4.15791533E-017 -1.1526424E-016
 -2.9580899E+001 1.96087156E+000 6.17751181E-001 1.94904727E+001 2.72998314E+002 6.65311589E+003 7.48207919E-016 4.15791533E-017 1.00000000E+000 -2.7565840E-017
 3.23332598E-002 -6.0960889E-001 6.75836334E-004 -5.9363743E+000 -1.3422938E-001 1.71416570E+000 1.67305948E-017 -1.1526424E-016 -2.7565840E-017 1.00000000E+000
2 Damping
 2.30014651E+005 -8.8056546E-001 2.73905735E+000 -1.0686895E+003 -2.1495767E+006 2.16103396E+002 7.21022144E+000 -1.2172153E+000 -2.9845145E-001 3.34978662E-004
 -8.8056546E-001 2.30014572E+005 5.39815481E+000 2.14957555E+006 -1.0677873E+003 -1.0036229E+002 -1.2166236E+000 -7.2165288E+000 1.97746907E-002 -6.1427539E-003
 2.73905735E+000 5.39815481E+000 2.66658961E+006 -6.8673664E-002 -6.1972576E-001 9.53428551E+003 -7.8354582E-004 -1.3216469E-003 6.21760169E-003 -1.9992808E-005
 -1.0686895E+003 2.14957555E+006 -6.8673664E-002 1.34219958E+008 1.54179569E+001 -7.7618682E+002 -1.1270390E+001 -6.6634309E+001 1.96643130E-001 -5.9907477E-002
 -2.1495767E+006 -1.0677873E+003 -6.1972576E-001 1.54179569E+001 1.34219972E+008 -2.0130405E+003 -6.6577559E+001 1.12699960E+001 2.75437191E+000 -1.3477097E-003
 2.16103396E+002 -1.0036229E+002 9.53428551E+003 -7.7618682E+002 -2.0130405E+003 4.28316981E+007 3.10727521E+000 -2.3570440E-001 6.71249946E+001 1.72836056E-002
 7.21022144E+000 -1.2166236E+000 -7.8354582E-004 -1.1270390E+001 -6.6577559E+001 3.10727521E+000 4.94181298E-001 8.41779784E-009 1.51759672E-009 1.35134654E-008
 -1.2172153E+000 -7.2165288E+000 -1.3216469E-003 -6.6634309E+001 1.12699960E+001 -2.3570440E-001 8.41779784E-009 4.94256042E-001 8.96350078E-009 -2.6595413E-009
 -2.9845145E-001 1.97746907E-002 6.21760169E-003 1.96643130E-001 2.75437191E+000 6.71249946E+001 1.51759672E-009 8.96350078E-009 5.30106659E-001 -2.8307917E-009
 3.34978662E-004 -6.1427539E-003 -1.9992808E-005 -5.9907477E-002 -1.3477097E-003 1.72836056E-002 1.35134654E-008 -2.6595413E-009 -2.8307917E-009 6.77540383E-001
3 Stiffness
 8.92893970E+007 -3.7455414E-001 -2.6087073E+000 -4.3007672E+005 -8.4071881E+008 -1.8168755E+001 -1.1415774E-002 6.92146114E-004 1.90860344E-004 3.55131325E-003
 -3.7455414E-001 8.92893975E+007 4.33235800E+000 8.40718801E+008 -4.3007024E+005 1.76983500E+001 4.22479955E-003 1.23558569E-002 -3.7390850E-003 3.16346777E-003
 -2.6087073E+000 4.33235800E+000 1.07931656E+009 1.46177482E+001 2.56746494E+000 3.84538911E+006 -1.2036368E-002 4.67362554E-003 -6.1249116E-003 -1.0872873E-002
 -4.3007672E+005 8.40718801E+008 1.46177482E+001 5.41691654E+010 -1.4262382E+001 1.89009898E+002 1.98381877E-002 1.36561295E-001 -1.2107673E-003 -5.4117086E-003
 -8.4071881E+008 -4.3007024E+005 2.56746494E+000 -1.4262382E+001 5.41691655E+010 2.05779454E+002 1.37819944E-001 -4.3953815E-002 -9.9030335E-004 2.66711566E-003
 -1.8168755E+001 1.76983500E+001 3.84538911E+006 1.89009898E+002 2.05779454E+002 1.71783287E+010 -4.1180337E-002 -9.7406520E-002 -2.3975125E-001 -4.5438092E-003
 -1.1415774E-002 4.22479955E-003 -1.2036368E-002 1.98381877E-002 1.37819944E-001 -4.1180337E-002 1.96313511E+002 3.41366436E-006 6.15430059E-007 5.48010728E-006
 6.92146114E-004 1.23558569E-002 4.67362554E-003 1.36561295E-001 -4.3953815E-002 -9.7406520E-002 3.41366436E-006 1.96343822E+002 3.63496294E-006 -1.0785222E-006
 1.90860344E-004 -3.7390850E-003 -6.1249116E-003 -1.2107673E-003 -9.9030335E-004 -2.3975125E-001 6.15430059E-007 3.63496294E-006 2.10882300E+002 -1.1479692E-006
 3.55131325E-003 3.16346777E-003 -1.0872873E-002 -5.4117086E-003 2.66711566E-003 -4.5438092E-003 5.48010728E-006 -1.0785222E-006 -1.1479692E-006 2.70671007E+002
4 Gravity load vector [N]/[Nm]
0.00000000E+000
0.00000000E+000
0.00000000E+000
0.00000000E+000
0.00000000E+000
0.00000000E+000
0.00000000E+000
0.00000000E+000
0.00000000E+000
```

Figure 6: Superelement .SMAT file generated from binary ROSA SEB-file. For display purposes, only the first 10 modes are shown.

The upper $6{\times}6$ block matrices are associated with the three translational and three rotational degrees of freedom for the interface node, retained in the superelement.

Additionally, the .SMAT file contains a set of simulation specific parameters, which are used to ensure that the exact same model and hydrodynamic loads are combined with the interface loads in the recovery-run. These can be identified as the lines starting with !SHEILAPM. An example of this is shown below, in Figure 7.

```
!SHEILAPM LCMB          0001
!SHEILAPM DLC_NUM       61_0_00
!SHEILAPM ANLYTYP       EXTREME
!SHEILAPM SGRP          0001
!SHEILAPM WIM           ETM
!SHEILAPM EXTCOND       DEFAULT
!SHEILAPM WISPEED       46.1000
!SHEILAPM ITURBLONG     0.1000000
!SHEILAPM WISHEAR       0.10000
!SHEILAPM WISEED        00000A
!SHEILAPM WIDIRM        000.00
!SHEILAPM YAWERR        0000.0
!SHEILAPM WVM           ESS
!SHEILAPM HSIGN         07.50
```

Figure 7: Simulation parameters included in the SMAT-file.

It should be noted that the superelement matrices are unique for each load case to properly account for the hydrodynamic added/contained mass for the associated water depth. Furthermore, the inherent linearisation e.g. of the pile-soil interaction may depend on the load level and thus be different for the various load cases.

The wave load files with file ending .WLVEC, contain the reduced wave load time series as well as the surface elevation. An example is shown in Figure 8.

```
8
0      36 ULS_SE_3X4L_0001_ro
0.0
   8001
    0.0000  5.85667731E+002 -2.9588147E+000 -3.3756646E+003 7.40691945E+001 -5.1330727E+003 1.39415993E+002 5.44509319E-001 -9.7395631E-002 -3.5581152E-003 1.04621484E-001
    0.1000  5.42893683E+002 -2.8282050E+000 -3.3791455E+003 7.43202108E+001 -4.7588557E+003 1.40463101E+002 5.06972024E-001 -9.1106649E-002 -1.9941382E-003 1.06933103E-001
    0.2000  4.97569086E+002 -2.7105054E+000 -3.3824123E+003 7.43351212E+001 -4.3637629E+003 1.40303374E+002 4.68003163E-001 -8.4557562E-002 -4.7296316E-004 1.08570309E-001
    0.3000  4.51858325E+002 -2.5980514E+000 -3.3849704E+003 7.42480425E+001 -3.9656427E+003 1.38930446E+002 4.28581707E-001 -7.7921339E-002 9.63467251E-004 1.09582538E-001
    0.4000  4.05211689E+002 -2.4616360E+000 -3.3865093E+003 7.42900235E+001 -3.5593908E+003 1.37183568E+002 3.88578820E-001 -7.1185513E-002 2.38164338E-003 1.10037522E-001
    0.5000  3.57864653E+002 -2.3619427E+000 -3.3870163E+003 7.47490888E+001 -3.1463754E+003 1.35020186E+002 3.48140946E-001 -6.4417847E-002 3.77607926E-003 1.09845073E-001
    0.6000  3.10880433E+002 -2.3203261E+000 -3.3866610E+003 7.50564482E+001 -2.7353110E+003 1.32488406E+002 3.07893283E-001 -5.7678047E-002 5.13076571E-003 1.09051390E-001
    0.7000  2.63253205E+002 -2.2665681E+000 -3.3855745E+003 7.54320489E+001 -2.3194878E+003 1.29825873E+002 2.67653657E-001 -5.0936265E-002 6.46635559E-003 1.07644421E-001
    0.8000  2.14822901E+002 -2.2255311E+000 -3.3835003E+003 7.56988781E+001 -1.8970383E+003 1.26384730E+002 2.27440794E-001 -4.4180620E-002 7.73088057E-003 1.05666646E-001
    0.9000  1.68771421E+002 -2.2069903E+000 -3.3812698E+003 7.57859017E+001 -1.4941842E+003 1.21576354E+002 1.88532012E-001 -3.7633563E-002 8.81998463E-003 1.02995193E-001
    1.0000  1.30418515E+002 -2.1972001E+000 -3.3804825E+003 7.58197227E+001 -1.1549803E+003 1.16984191E+002 1.53148788E-001 -3.1694176E-002 9.76849126E-003 9.97531682E-002
    1.1000  9.45529866E+001 -2.2158383E+000 -3.3801330E+003 7.55499631E+001 -8.3712852E+002 1.11443812E+002 1.19387526E-001 -2.6012060E-002 1.05556784E-002 9.60153008E-002
```

Figure 8: Superelement .WLVEC file generated from binary ROSA SEB-file. For display purposes only the first 10 modes are shown.

It should be noted that the units in the reduced wave load data file (WLVEC file) are kN and KNm, while the superelement matrices in the SMAT file are in SI units, i.e. N, m, etc.

5 VERIFYING SUPERELEMENT CONVERGENCE

As a consequence of reducing the full jacket model into a superelement, the dynamic behaviour of the jacket is approximated since the superelement only includes a limited number of deformation modes. Thus, it must be ensured that the superelement accurately represents both the dynamic behaviour of the full model, as well as the external loading, i.e. both spectral and spatial convergence must be verified.

For the present study, a Craig-Bampton superelement of size 36 x 36 is used, corresponding to the 6 static constraint modes (Guyan [3]) and 30 internal fixed interface modes.

5.1 Spectral convergence

To accurately capture the interaction between the foundation and the superstructure, it must be verified that the superelement accurately represents the frequency content of the full model, well above the expected frequency content of the external excitation. The first 30 free interface natural frequencies for the stand-alone jacket structure are listed in Table 2. The maximum error is below 0.9%, for the first 20 mode, up to a frequency just over 7 Hz.

Table 2: Comparison of free interface natural frequencies for stand-alone jacket.

Mode	ROSA [Hz]	ROSA (SE) [Hz]	Error [%]	Bladed (SE) [Hz]	Error [%] vs ROSA (SE)
1	1.3212	1.3216	0.0282	1.3216	0.000
2	1.3212	1.3216	0.0289	1.3216	0.000
3	1.8531	1.8531	0.0023	1.8531	0.000
4	2.6184	2.6184	0.0000	2.6184	0.000
5	2.8564	2.8577	0.0466	2.8577	0.000
6	2.8564	2.8577	0.0468	2.8577	0.000
7	2.8950	2.8950	0.0000	2.8950	0.000
8	2.9464	2.9464	0.0000	2.9464	0.000
9	3.7838	3.7838	0.0000	3.7838	0.000
10	4.1102	4.1110	0.0186	4.1110	0.000
11	4.1106	4.1114	0.0181	4.1114	0.000
12	4.1834	4.1837	0.0069	4.1837	0.000
13	4.3584	4.3959	0.8597	4.3959	0.000
14	4.3604	4.3994	0.8923	4.3994	0.000
15	4.9214	4.9300	0.1761	4.9300	0.000
16	5.5591	5.5591	0.0002	5.5591	0.000
17	5.8261	5.8533	0.4680	5.8533	0.000
18	5.8269	5.8535	0.4573	5.8535	0.000
19	6.5566	6.5618	0.0793	6.5619	0.002
20	7.1981	7.1987	0.0074	7.1987	0.000
21	7.2102	7.2981	1.2184	7.2981	0.000
22	7.8051	7.8075	0.0306	7.8075	0.000
23	7.8054	7.8076	0.0276	7.8076	0.000
24	8.0882	8.3075	2.7114	8.3075	0.000
25	8.0912	8.4077	3.9118	8.4077	0.000
26	8.3076	8.4236	1.3959	8.4236	0.000
27	8.3923	8.4912	1.1792	8.4913	0.001
28	8.4829	8.4969	0.1643	8.4969	0.000
29	8.7413	8.7413	0.0002	8.7413	0.000
30	9.0180	9.0246	0.0743	9.0247	0.001

5.2 Spatial convergence

Besides the ability to accurately represent the dynamic behaviour of the foundation in terms of frequencies, it must be ensured that the superelement captures the spatial distribution of the external loading. A comparison of the interface response for the stand-alone jacket subject to gravitational and hydrodynamic loads only are presented in Figure 9, for both the full foundation model and a reduced superelement model in ROSA. A good correspondence is seen in all displacement components.

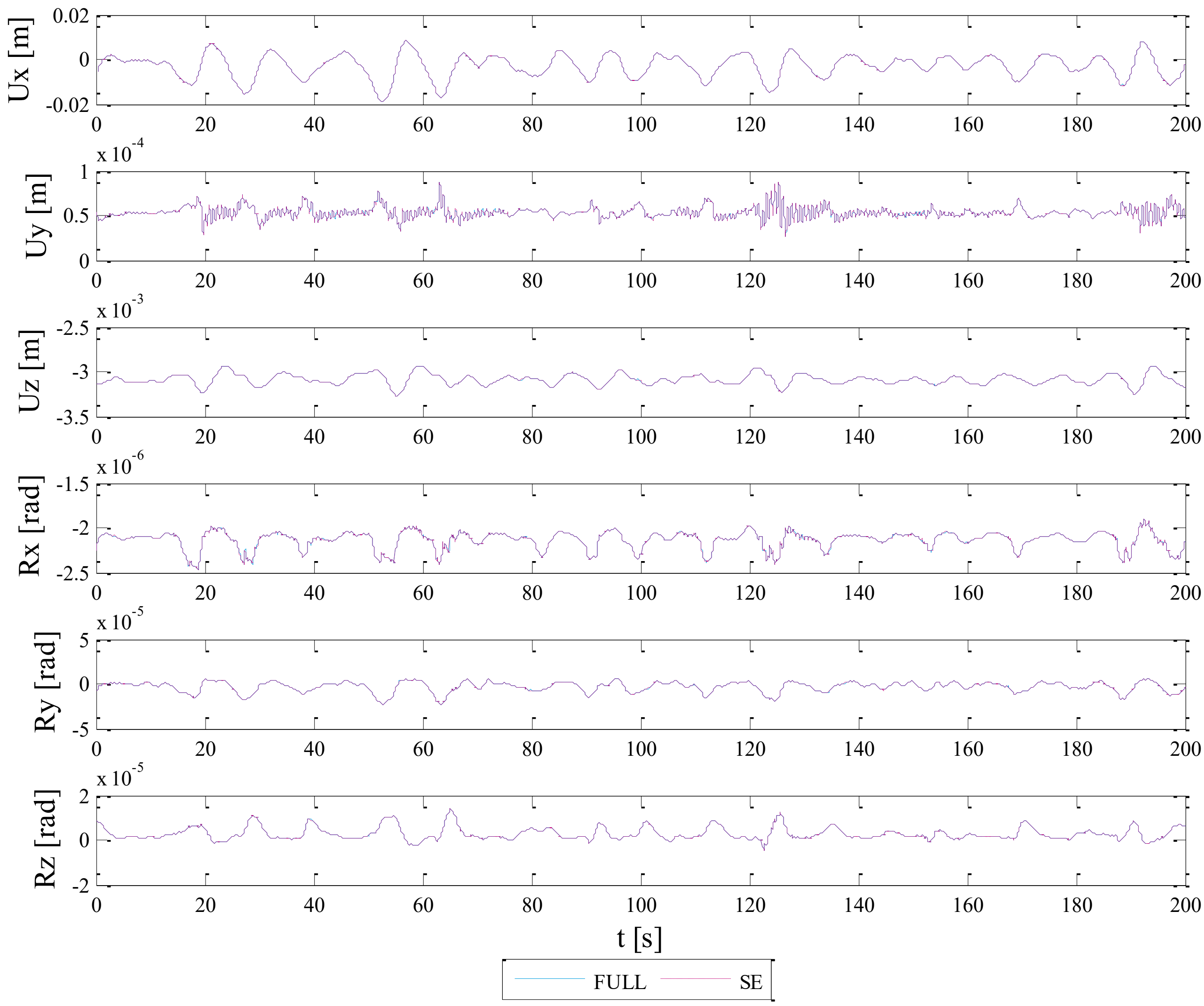

Figure 9: Illustration of the spatial convergence.

Only the response to gravity and hydrodynamic loads are considered here, since the accuracy of the response to excitations applied at the interface node(s) is/are closely related to the spectral convergence.

When considering the response of a superelement to a harmonic excitation with frequency Ω, the steady state amplitude A will depend on how well the superelement represents the dynamic (modal) properties the underlying "full" model. The accuracy of forced vibration will thus be of the same order as the accuracy of the natural frequencies/modes. This information is readily available by considering the frequency response function

$$A = \frac{1}{\sqrt{\left(\tilde{\omega}_j - \Omega\right)^2 + \left(2\,\tilde{\zeta}_j\,\tilde{\omega}_j\Omega\right)^2}}$$

where $\tilde{\omega}_j$ and $\tilde{\zeta}_j$ denote the natural frequency and damping ratio associated with mode j, as predicted by the superelement.

5.3 Structural damping

The damping matrix in ROSA is modelled through the Rayleigh damping approach, with contributions proportional to the mass and stiffness

$$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}$$

Therefore, if only stiffness proportional damping is included, the coupling to the internal modes appears solely through the mass coupling terms (the mass matrix is non-diagonal). Since Rayleigh damping is a linear combination of the system mass and stiffness matrices, the same linear combination is valid for the reduced superelement matrices with subscript SE, i.e.

$$\mathbf{C}_{SE} = \mathbf{T}^T\mathbf{C}\,\mathbf{T} = \mathbf{T}^T(\alpha\mathbf{M} + \beta\mathbf{K}\,)\mathbf{T} = \alpha\mathbf{T}^T\mathbf{M}\,\mathbf{T} + \beta\mathbf{T}^T\mathbf{K}\,\mathbf{T} = \alpha\mathbf{M}_{SE} + \beta\mathbf{K}_{SE}$$

Therefore, the accuracy of the damping ratio ζ_j (for mode j) achieved via Rayleigh damping, which can be expressed as

$$\zeta_j = \frac{1}{2}\left(\frac{\omega_j}{\alpha} + \beta\omega_j\right)$$

depends on how well the condensed model (superelement) represents the frequencies of the full model.

6 RESULT COMPARISON

In the following sections, the results from the verification study are presented in terms of the generalised displacement, velocity and acceleration time series, at the interface as well as selected key locations in the foundation structure.

6.1 Interface displacement

A comparison of the time series for the interface displacement/rotations obtained in ROSA and Bladed, respectively, are shown in Figure 10. Furthermore, a comparison of the associated frequency spectra is illustrated in Figure 11. It is seen that results match very well in both time and frequency domains.

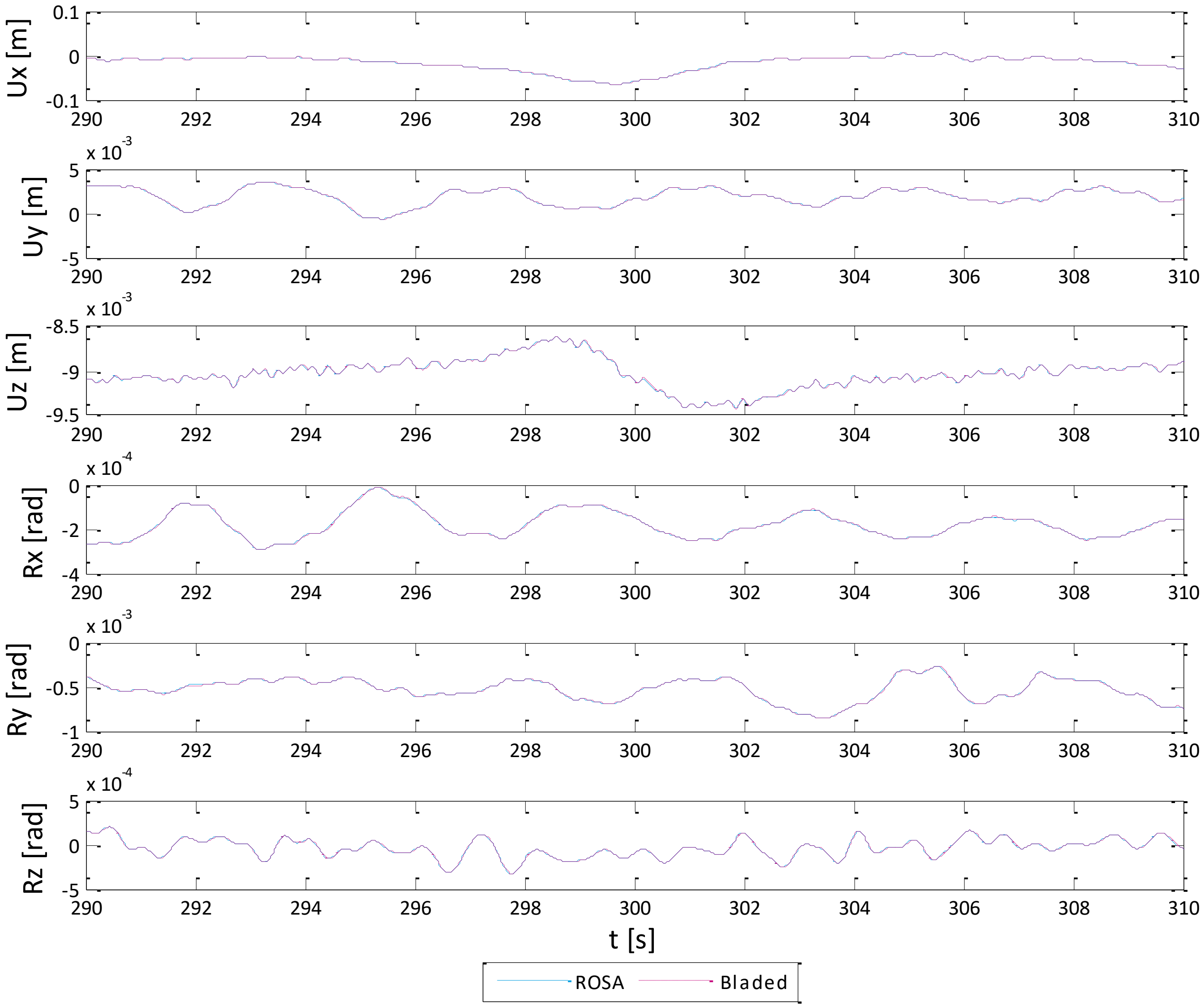

Figure 10: Time series comparison of interface response from ROSA and Bladed.

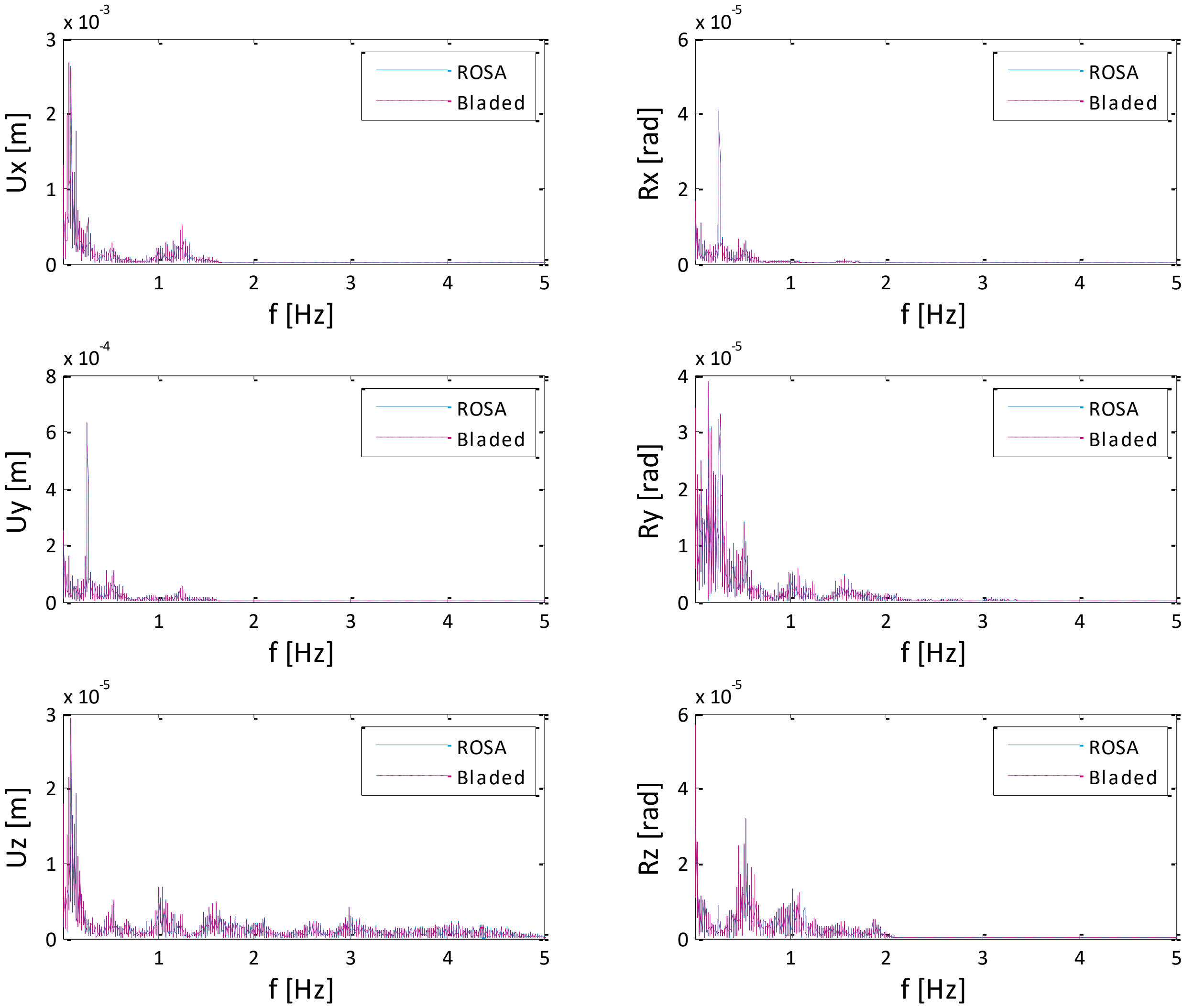

Figure 11: Frequency spectra comparison of interface response between ROSA and Bladed.

6.2 Interface velocities

A comparison of the time series for the interface velocities obtained in ROSA and Bladed respectively, are shown in Figure 12. Furthermore, a comparison of the associated frequency spectra is illustrated in Figure 13. It is seen that the results match very well in both time and frequency domains.

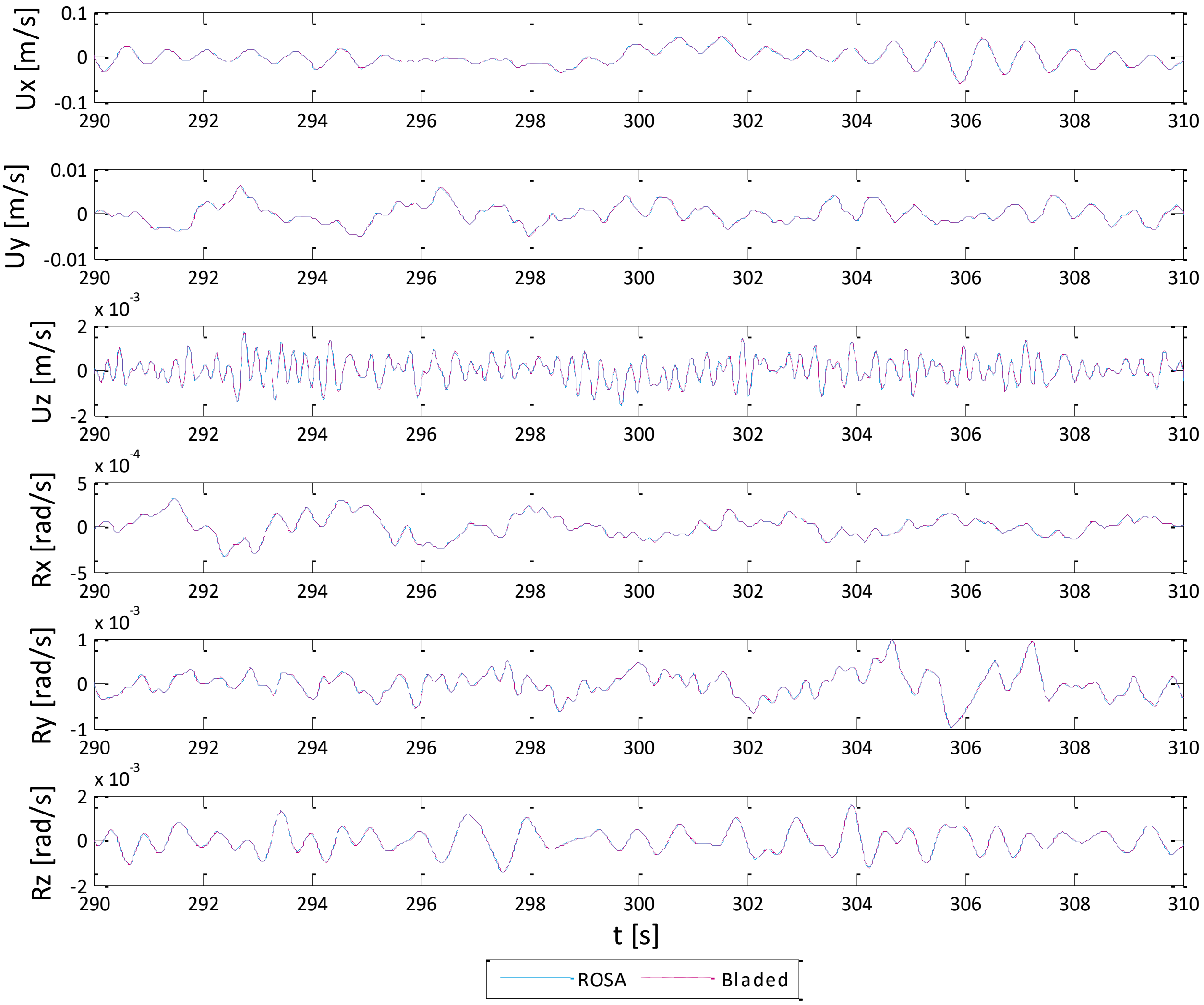

Figure 12: Time series comparison of interface velocities between ROSA and Bladed.

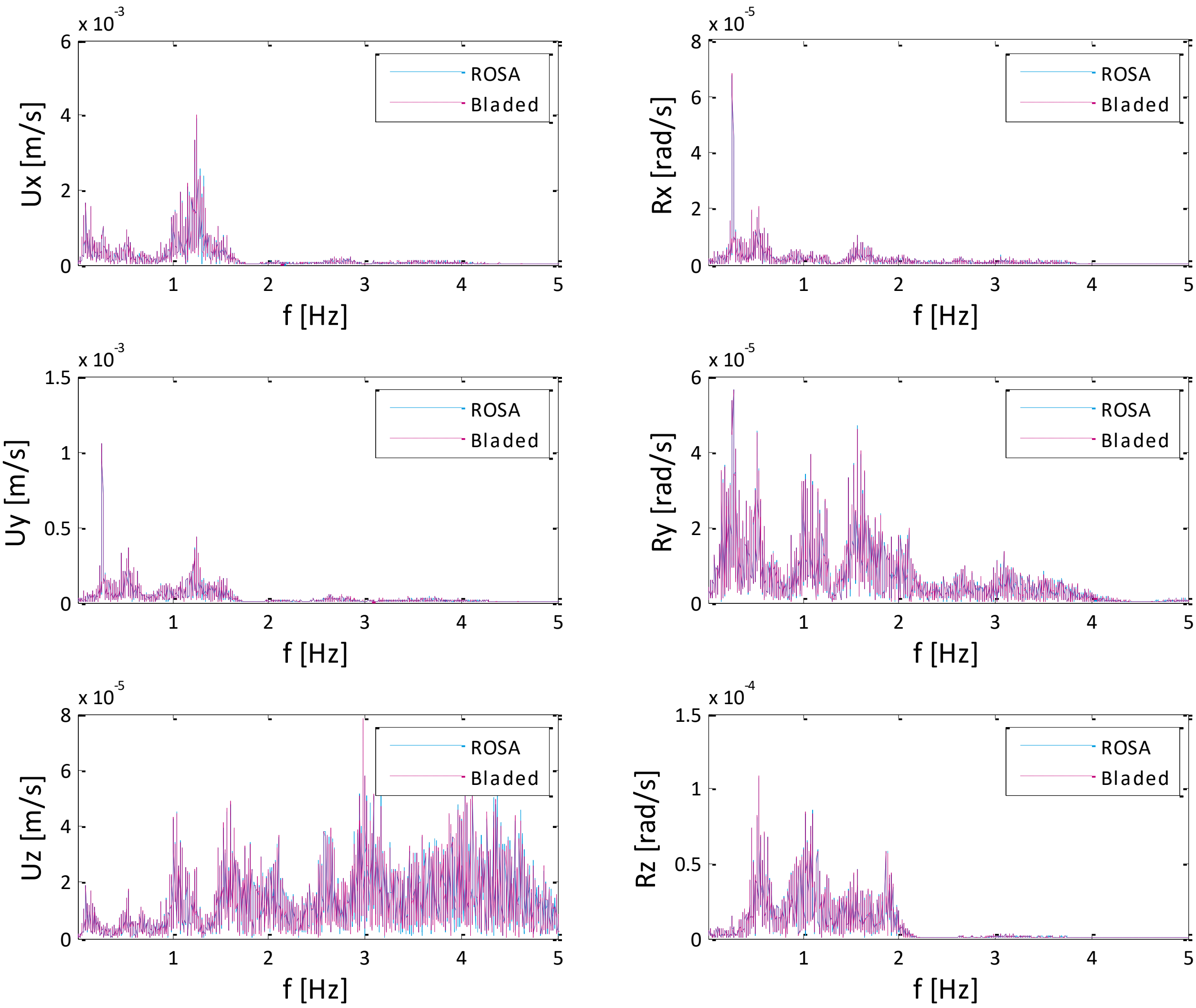

Figure 13: Frequency spectra comparison of interface velocities between ROSA and Bladed.

6.3 Interface accelerations

A comparison of the time series for the interface accelerations obtained in ROSA and Bladed, respectively, are shown in Figure 14. Furthermore, a comparison of the associated frequency spectra is illustrated in Figure 15. It is seen that results are acceptably similar in both time and frequency domains. However, due to the high frequency content present in the accelerations, and the fact that these are the second derivatives of the primary variables (displacements/rotations); they are very sensitive to the accuracy of the interface loads. Hence it is of utmost importance that loads are exchanged with a sufficient level of precision, if accelerations are to be recovered correctly.

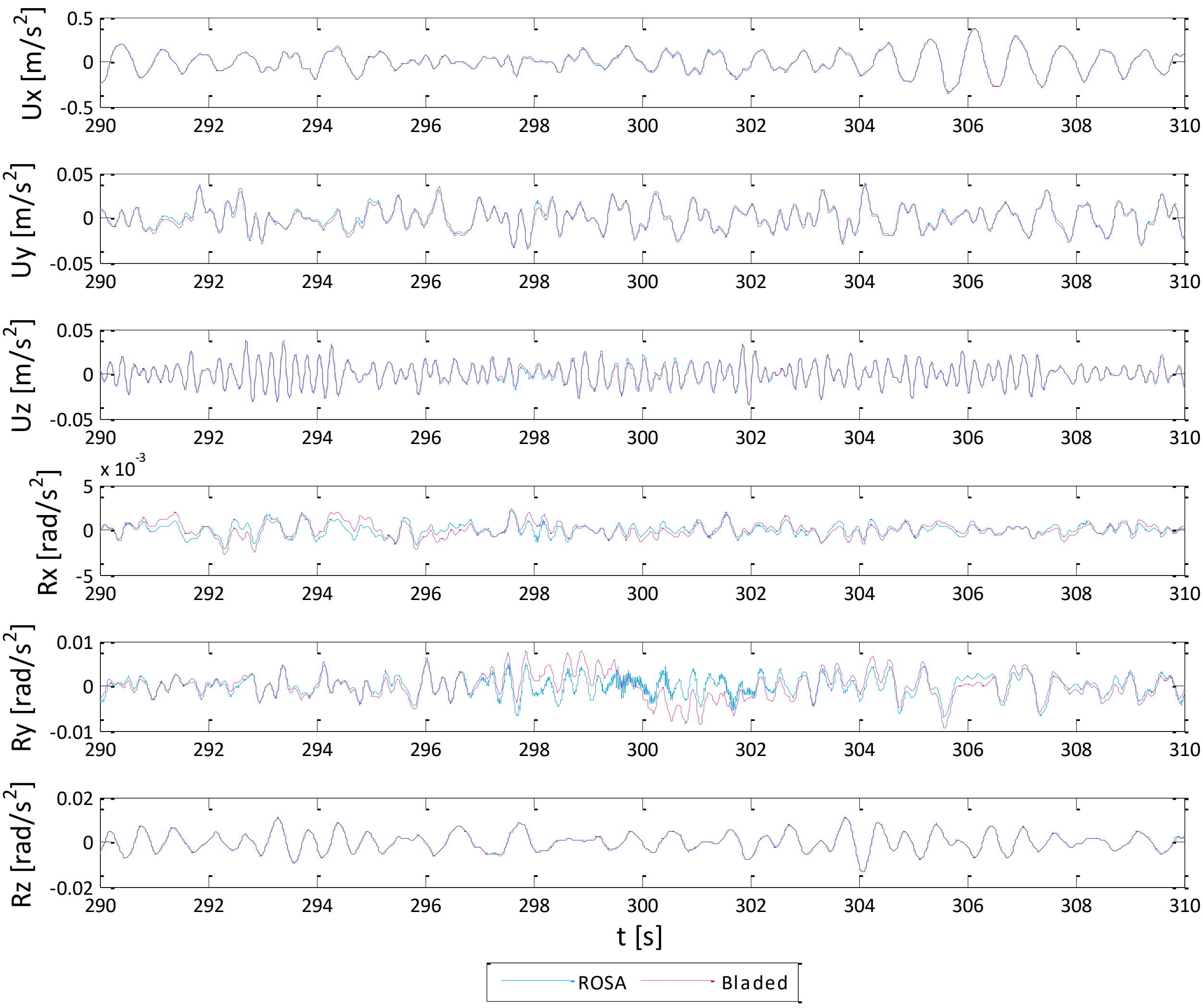

Figure 14: Comparison of interface accelerations between ROSA and Bladed.

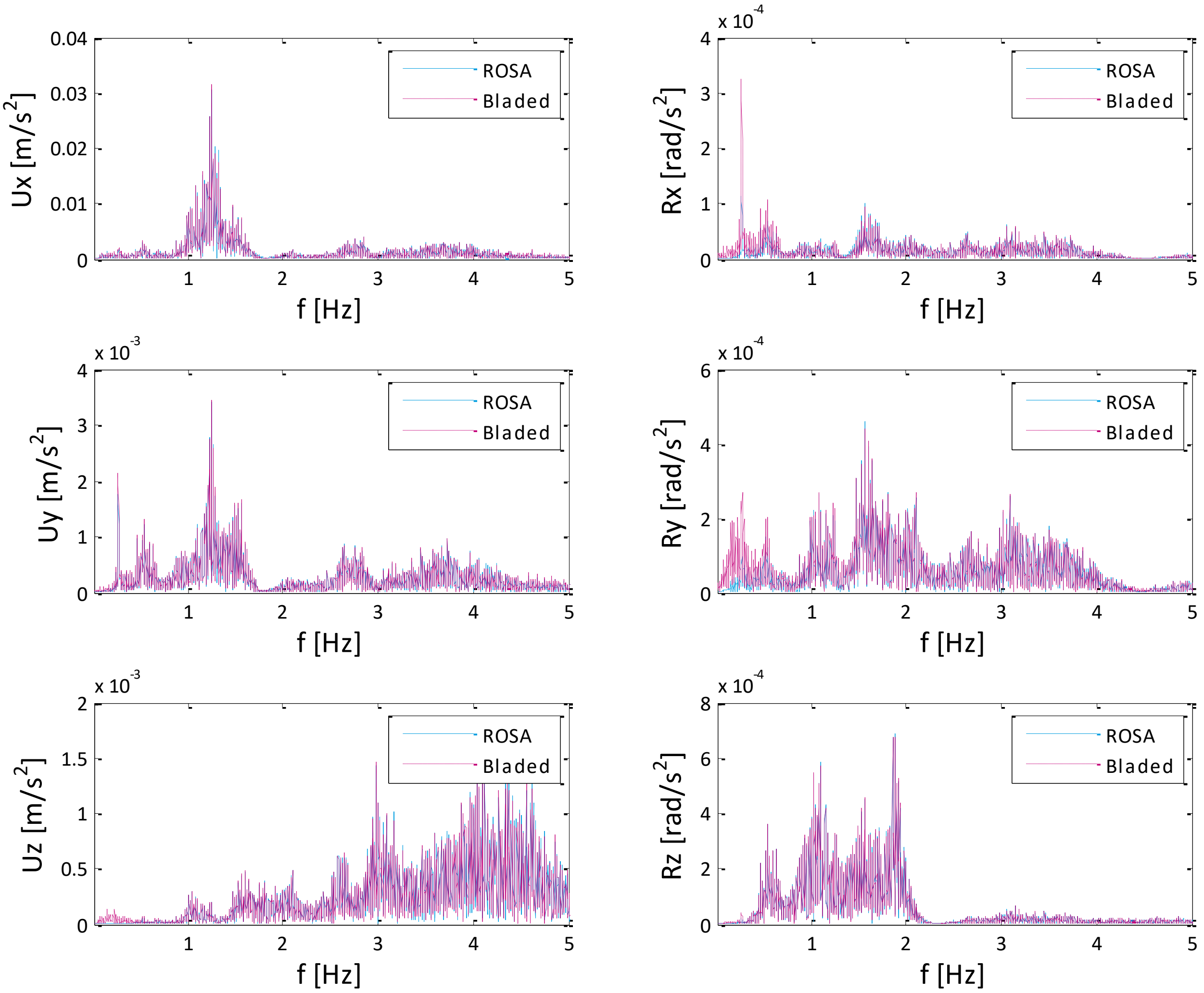

Figure 15: Frequency spectra comparison of interface accelerations from ROSA and Bladed.

6.4 Internal response

Besides a good match on the response at the interface nodes, it has been verified that the response at the selected internal nodes within the jacket structure agrees, for the two different models. The x-displacement (out-of-plane) at the locations illustrated in Figure 16 are considered.

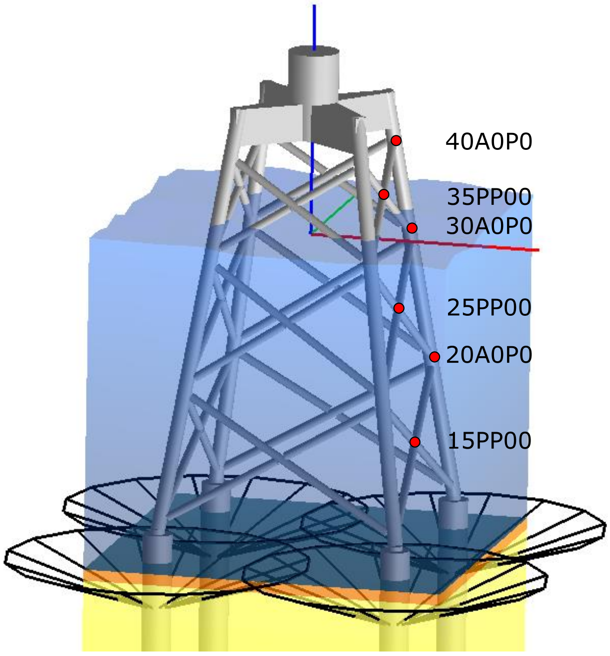

Figure 16: Selected key location in the jacket.

In ROSA, the results are readily available from a dynamic time domain analysis for the full model, while the Bladed results can be found via direct expansion of the interface DOFs (and the generalised displacements associated with the Craig-Bampton modes). As illustrated in Figure 17, a good agreement is found for all locations, which confirms the spatial convergence of the superelement model for the integrated analysis.

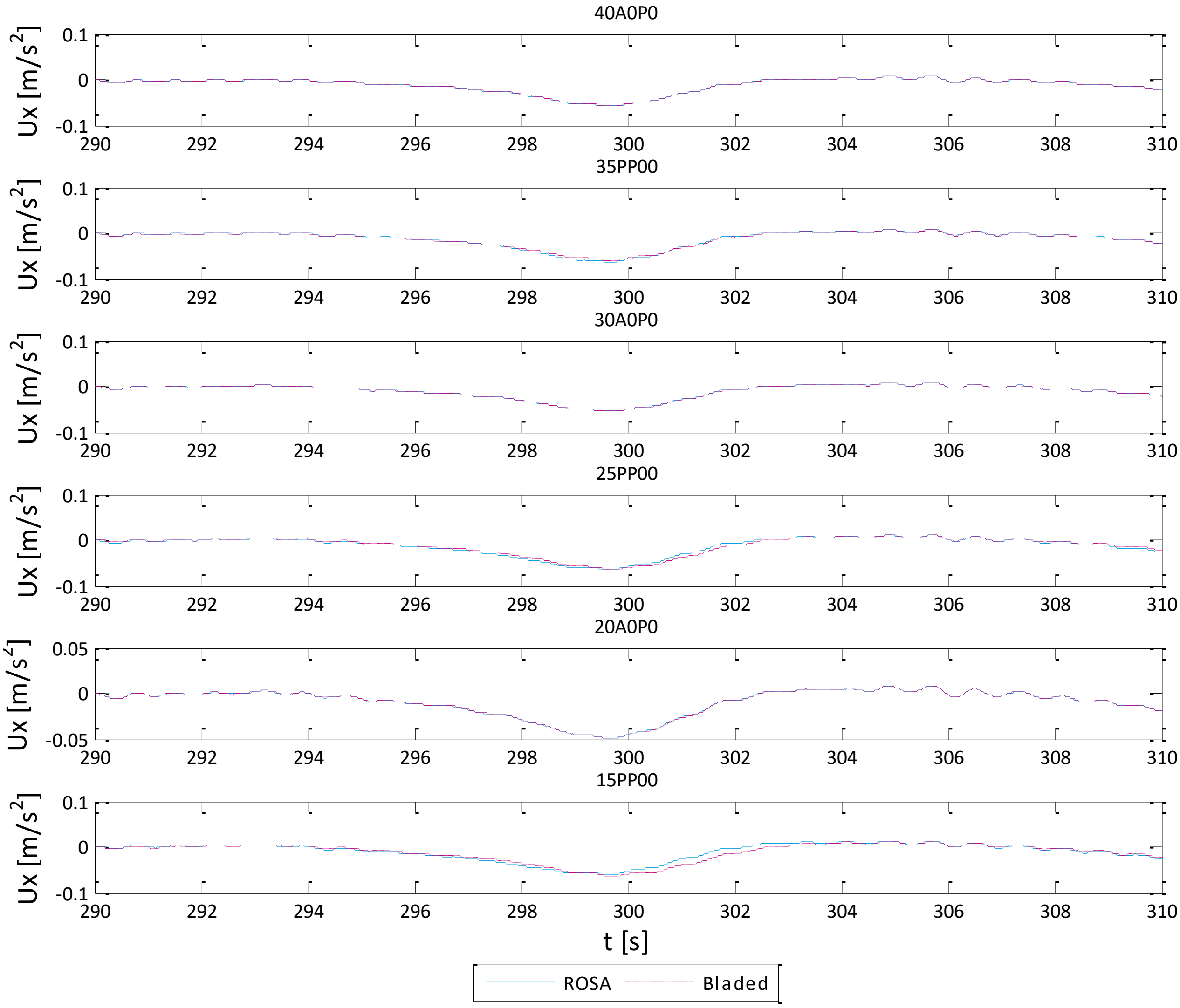

Figure 17: Comparison of x-displacement at the selected internal nodes, between ROSA and Bladed.

7 CONCLUSIONS AND RECOMMENDATIONS

The superelement interface method has been verified between Bladed and ROSA, for an offshore jacket model and a generic 7MW wind turbine.

It is confirmed that the ROSA superelement and reduced wave load files can be correctly read by Bladed. The coordinate transformation required between ROSA and Bladed is handled correctly, facilitating the superelement import into Bladed, and the interface load export from Bladed.

The reported superelement jacket frequencies in ROSA and Bladed are almost identical. Time histories and spectra of interface kinematics in the coupled Bladed simulation and ROSA recovery-run correspond extremely well. Interface accelerations show a reasonable match, with some higher frequency excitation only present in ROSA.

8 REFERENCES

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