WHEN TRUST MATTERS

BLADED: LOCAL JOINT FLEXIBILITIES VERIFICATION REPORT

Report No. 2022-9773

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Verification Report

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1 INTRODUCTION

The substructure of a fixed offshore platform is generally made up of steel tubular members that are connected at joints. When a jacket structure is modelled using beam elements, the joints are typically represented as rigid connections, i.e. the member rotations immediately outside the joints are fixed, and all the model flexibility is provided by the beams only. However, in reality, tubular joints exhibit some degree of flexibility due to the local distortions of the cross-sections of members in a joint, and hence resulting in some degree of compliance. This compliance is known as Local Joint Flexibility (LJF) and is demonstrated in Figure 1-1.

Accounting for LJFs enhances the model fidelity and can improve the accuracy of beam section forces, deflections and natural frequency to better represent real structures. Modern Design codes such as API and DNV recommend that the LJF effects should be engaged in global analyses of the structures. Appendix B in DNV-OS-J101 /1/ explains how local joint flexibilities can be simulated using spring elements based on Buitrago's parametric equations /2/.

Buitrago's parametric equations return spring stiffness values based on the geometry of the members and the pattern of force flow within a joint. The joint flexibility hence is accounted for in three directions: axial, in-plane-bending, and out-of-plane bending.

The Bladed Hinges feature allows the user to define joint flexibility properties at one or both ends of each beam member in a multi-member support structure. Up to 6 stiffness components (3 translational and 3 rotational degrees of freedom) may be defined for each joint position. These components can be set as fixed, free, or with absolute spring stiffness in SI units. To model an LJF, 3 degrees of freedom are defined using Buitrago's equations, and the other three terms of the 6DOF spring are assumed to be rigid. It is possible to specify the spring properties in either the global coordinate system, a local coordinate system to which the hinge is assigned or a user-defined coordinate system.

The Hinges feature can also be combined with Member End Offsets (MEO), as shown in Figure 1-2, or used to model true hinges with rotational degrees of freedom fully released. Refer to Bladed User Manual /4/ for full details on the Hinges feature.

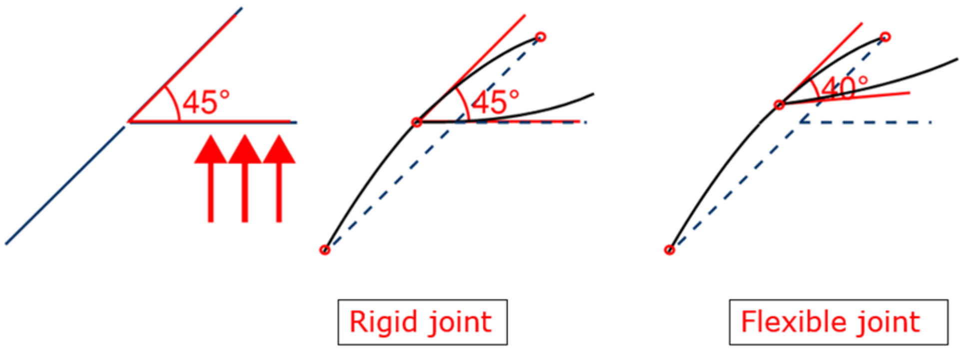
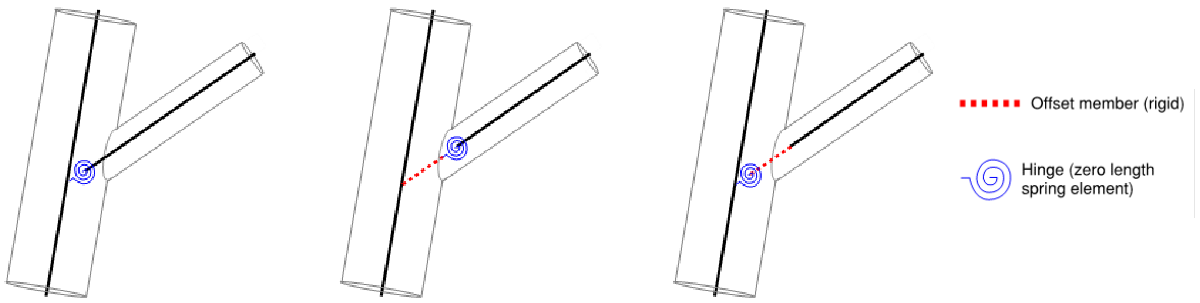


Figure 1-1 – Example effect of including Local Joint Flexibilities on structural deflection



(a) (b) (c)

Figure 1-2 – (a) Brace member end release or flexibility simulated by a zero-length 6DOF spring element. (b)(c) In combination with member end offset (MEO)

2 SCOPE AND OBJECTIVES

Modelling of LJFs in Bladed mirrors the same feature in Sesam /6/. This is to support the integrated design workflow, where the design of the jacket and tower can be completed in Sesam, then the model is converted into Bladed using Sesam Wind Manager. Coupled analysis of wind and wave loads is then performed in Bladed, after which load post-processing is performed in Sesam.

The objective of this report is to verify that the local joint flexibilities inhibit the same behaviour across Bladed and Sesam and return similar effects on the structure, including local stresses and global response. Analysis is therefore performed over test models of full-sized jacket structures. The validation of the Bladed implementation of LJFs is achieved by comparison of key Bladed results against Sesam using the same 3D jacket model that is described in the Verification report of Sesam's Bladed interface /1/ and also Member End Offsets verification report /7/.

The anticipated workflow is that LJFs will first be defined in Sesam, either via user-defined beam end 'Hinges' or using automated tools in Sesam GeniE (as exemplified in Figure 2-1). It will then be possible to convert the LJFs to Bladed model format using Sesam Wind Manager 6.0 or newer.

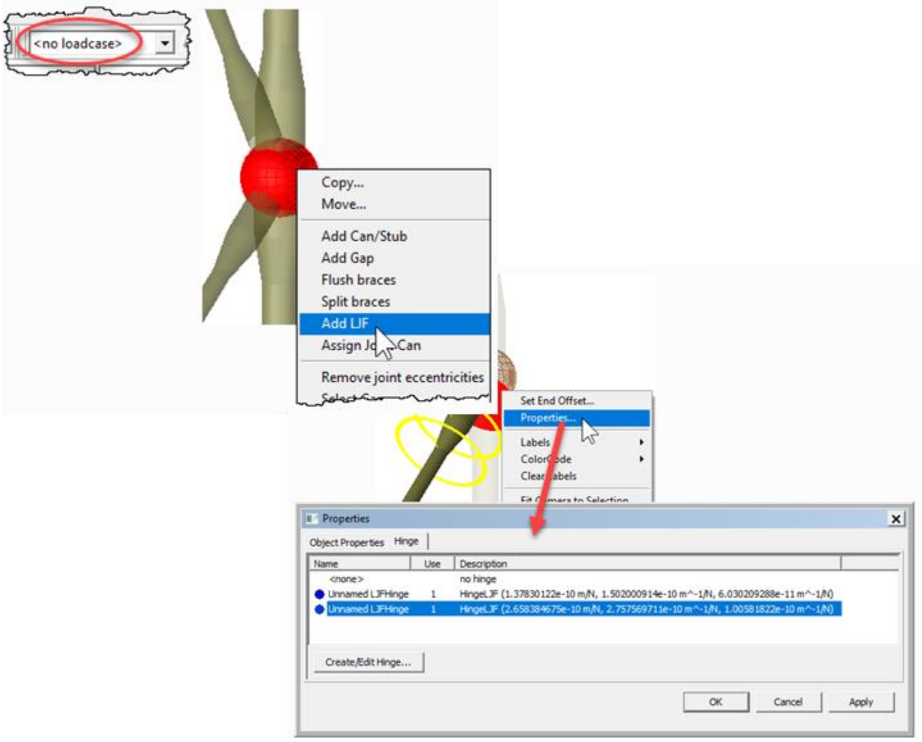


Figure 2-1 – Example of LJF automated generation in Sesam GeniE

3 MODEL SETUP

The LJF implementation in Bladed is compared against Sesam using the full 3D jacket model from verification reports /1/ and /7/ as a template.

Verification is be made based on the following comparisons between Sesam and Bladed:

1. A comparison of 'coupled' modal frequencies in Bladed against eigenvalue frequencies in Sesam
2. A comparison of shear forces / bending moments / reactions for members & locations described in section 5, for a Static loading scenario, including gravity, buoyancy and uniform current loading

Comparisons of key results will be made for the following two model variants:

1. Model with MEOs and **no** LJFs (the 'original' model described in /7/)
2. Model with MEOs and **with** LJFs
    - The Sesam model variant is created in Genie by selecting all joints in a copy of the original Genie model (1) and selecting 'add LJF'.

The Bladed models are created from the original Sesam jacket model (1) using the Sesam-Bladed converter tool in Sesam Wind Manager (SWiM 6.0). The 'tower' module of this converted Bladed model (which also includes the jacket structure) is then imported into a template Bladed model that has all Rotor Nacelle Assembly (RNA) properties set to zero. Figure 3-1 and Figure 3-2 show comparisons of the original Sesam model and the Bladed model after import.

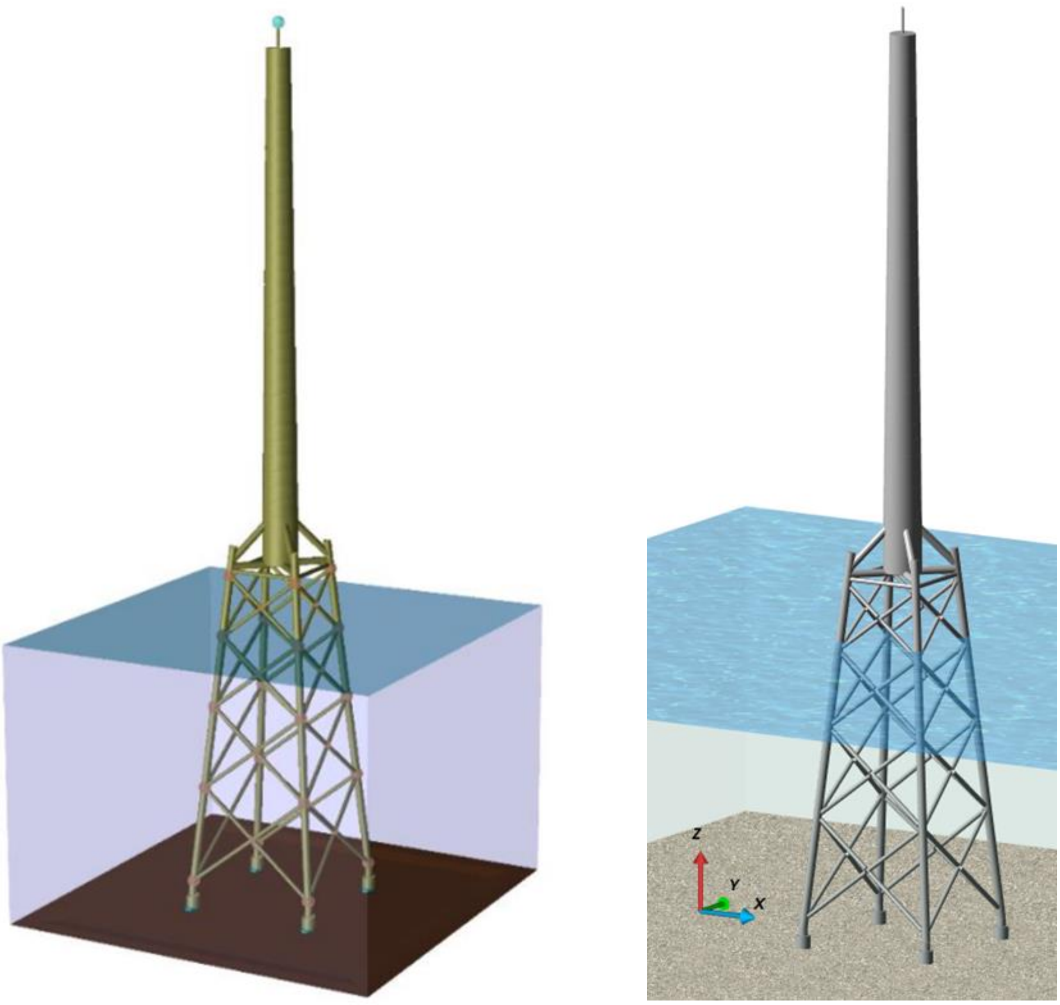


Figure 3-1 – Jacket models with member sections visualised, left-hand image shows the Sesam model and right-hand image shows the imported Bladed model in Bladed results viewer

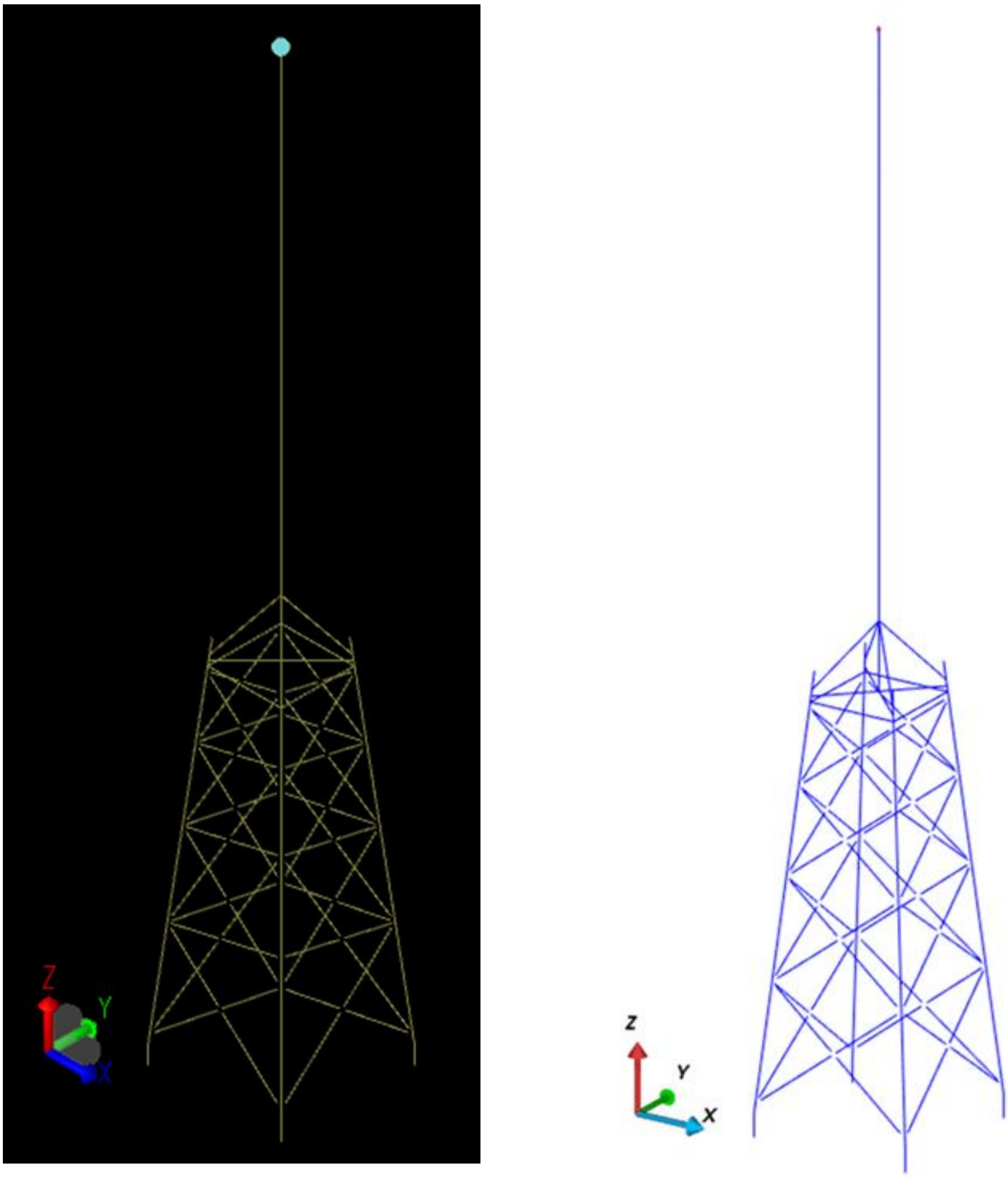


Figure 3-2 – Jacket models with offsets at member joints shown, left-hand image shows the Sesam model and right-hand image shows the imported Bladed model in Bladed results viewer

4 RESULTS: MODAL FREQUENCIES

Table 4-1 provides a comparison of modal frequencies, computed in Sesam and Bladed, for the full jacket model with MEOs, both with and without LJFs (i.e. model variants 1 & 2). The results show a very good match between Bladed and Sesam frequencies for both model variants, with the majority of results for the first 50 modes less than 0.01% and 0.5% between Bladed and Sesam. The results also demonstrate that the LJF has a very small influence on the lowest jacket modes, but significant influence on the higher modes, which are associated with local deflections of brace members.

The Bladed frequency results are computed as ‘coupled’ modes using ‘Campbell diagram’ type Model Linearisation analysis with a parked rotor and 0.01m/s wind speed. The Sesam frequency results are obtained from an eigenvalue analysis in Genie that includes a ‘wave load’ activity to apply effects of added mass (but not wave loading in this case). Effects of added mass perpendicular to members is included but the option to include longitudinal mass of internal water is switched off to match with the modelling behaviour in Bladed.

Table 4-1 – Sesam and Bladed natural frequency comparison with and without LJFs

	No-LJF			LJF			Change in frequency due to LJFs	
Number	Sesam (Hz)	Bladed (Hz)	% difference (Sesam-Bladed)	Sesam (Hz)	Bladed (Hz)	% difference (Sesam-Bladed)	Sesam	Bladed
1	0.281	0.281	**0.04%**	0.281	0.281	**0.01%**	0.01%	-0.02%
2	0.281	0.281	**0.00%**	0.281	0.281	**0.01%**	0.01%	0.02%
3	1.603	1.606	**-0.16%**	1.568	1.572	**-0.24%**	2.28%	2.19%
4	1.604	1.611	**-0.47%**	1.578	1.583	**-0.27%**	1.60%	1.80%
5	3.555	3.551	**0.11%**	3.475	3.472	**0.07%**	2.32%	2.27%
6	3.555	3.555	**0.01%**	3.492	3.491	**0.05%**	1.81%	1.85%
7	4.645	4.641	**0.09%**	4.566	4.590	**-0.53%**	1.74%	1.10%
8	5.281	5.305	**-0.44%**	4.615	4.638	**-0.48%**	14.42%	14.38%
9	5.537	5.549	**-0.20%**	4.642	4.639	**0.08%**	19.28%	19.62%
10	5.989	5.991	**-0.04%**	4.818	4.825	**-0.15%**	24.31%	24.17%
11	5.990	5.997	**-0.12%**	4.825	4.832	**-0.15%**	24.14%	24.10%
12	6.726	6.729	**-0.04%**	5.234	5.228	**0.12%**	28.52%	28.72%
13	7.305	7.329	**-0.34%**	6.120	6.132	**-0.20%**	19.36%	19.52%
14	7.587	7.582	**0.06%**	6.135	6.152	**-0.28%**	23.68%	23.26%
15	7.592	7.597	**-0.07%**	6.249	6.252	**-0.04%**	21.48%	21.51%
16	7.594	7.597	**-0.03%**	6.266	6.271	**-0.07%**	21.19%	21.14%
17	9.118	9.126	**-0.08%**	7.225	7.222	**0.04%**	26.20%	26.36%
18	9.139	9.145	**-0.07%**	7.454	7.455	**-0.02%**	22.61%	22.67%
19	9.826	9.880	**-0.55%**	7.504	7.507	**-0.05%**	30.95%	31.60%
20	9.890	9.897	**-0.06%**	8.319	8.322	**-0.03%**	18.89%	18.92%
21	10.016	9.999	**0.16%**	9.043	9.055	**-0.13%**	10.75%	10.43%
22	10.174	10.136	**0.37%**	9.191	9.195	**-0.04%**	10.69%	10.23%
23	10.174	10.139	**0.35%**	9.431	9.435	**-0.04%**	7.87%	7.46%
24	10.567	10.568	**-0.01%**	9.808	9.849	**-0.41%**	7.74%	7.31%
25	11.264	11.309	**-0.39%**	9.981	9.944	**0.37%**	12.86%	13.72%
26	11.871	11.904	**-0.28%**	10.029	9.989	**0.40%**	18.37%	19.17%
27	12.071	12.079	**-0.07%**	10.224	10.212	**0.12%**	18.06%	18.28%
28	12.073	12.097	**-0.20%**	10.579	10.634	**-0.52%**	14.12%	13.75%
29	12.313	12.313	**0.00%**	11.196	11.240	**-0.40%**	9.99%	9.54%
30	12.315	12.326	**-0.09%**	11.427	11.459	**-0.28%**	7.77%	7.57%
31	12.991	13.039	**-0.37%**	11.538	11.565	**-0.24%**	12.60%	12.74%
32	13.205	13.226	**-0.16%**	11.709	11.756	**-0.39%**	12.78%	12.51%
33	13.206	13.230	**-0.18%**	11.829	11.858	**-0.25%**	11.64%	11.57%
34	13.297	13.335	**-0.29%**	11.893	11.926	**-0.28%**	11.81%	11.82%
35	13.643	13.665	**-0.16%**	12.030	12.053	**-0.19%**	13.41%	13.38%
36	14.307	14.360	**-0.37%**	12.809	12.818	**-0.07%**	11.69%	12.03%
37	14.626	14.689	**-0.43%**	13.350	13.399	**-0.37%**	9.55%	9.62%
38	14.627	14.692	**-0.44%**	13.399	13.429	**-0.23%**	9.17%	9.40%

Number	No-LJF			LJF			Change in frequency due to LJFs	
	Sesam (Hz)	Bladed (Hz)	% difference (Sesam-Bladed)	Sesam (Hz)	Bladed (Hz)	% difference (Sesam-Bladed)	Sesam	Bladed
39	14.933	14.973	**-0.27%**	13.491	13.491	**0.00%**	10.69%	10.99%
40	15.349	15.403	**-0.36%**	13.528	13.549	**-0.16%**	13.46%	13.68%
41	15.818	15.930	**-0.70%**	13.627	13.674	**-0.35%**	16.08%	16.50%
42	17.063	17.072	**-0.05%**	13.727	13.787	**-0.44%**	24.30%	23.82%
43	17.134	17.277	**-0.83%**	13.771	13.792	**-0.15%**	24.42%	25.27%
44	17.139	17.299	**-0.92%**	14.522	14.535	**-0.09%**	18.02%	19.01%
45	17.287	17.315	**-0.16%**	14.594	14.690	**-0.65%**	18.45%	17.86%
46	17.288	17.340	**-0.30%**	15.192	15.335	**-0.93%**	13.80%	13.08%
47	17.534	17.733	**-1.12%**	15.452	15.550	**-0.63%**	13.48%	14.04%
48	17.724	17.751	**-0.15%**	15.550	15.655	**-0.67%**	13.98%	13.39%
49	17.961	17.988	**-0.15%**	15.733	15.821	**-0.55%**	14.16%	13.70%
50	17.961	17.990	**-0.16%**	15.829	15.985	**-0.98%**	13.47%	12.54%

5 RESULTS: STATIC LOAD SIMULATIONS

5.1 Locations for result extraction

Figure 5-1 and Figure 5-2 show the element numbering for selected members that are used for comparisons of member loads between Sesam and Bladed.

Each of the jacket X brace members includes a short ‘stub’ section at the intersection with the jacket legs, so there are 3 ‘beam concepts’ per brace member in the Sesam model. A mesh definition assignment of 1 element per beam concept is assigned to all of the jacket members, resulting in 6 elements in total across the X joint, as illustrated by the right-hand image in Figure 5-1.

Pile cap reactions are checked using member loads extracted for the members shown in Figure 5-2.

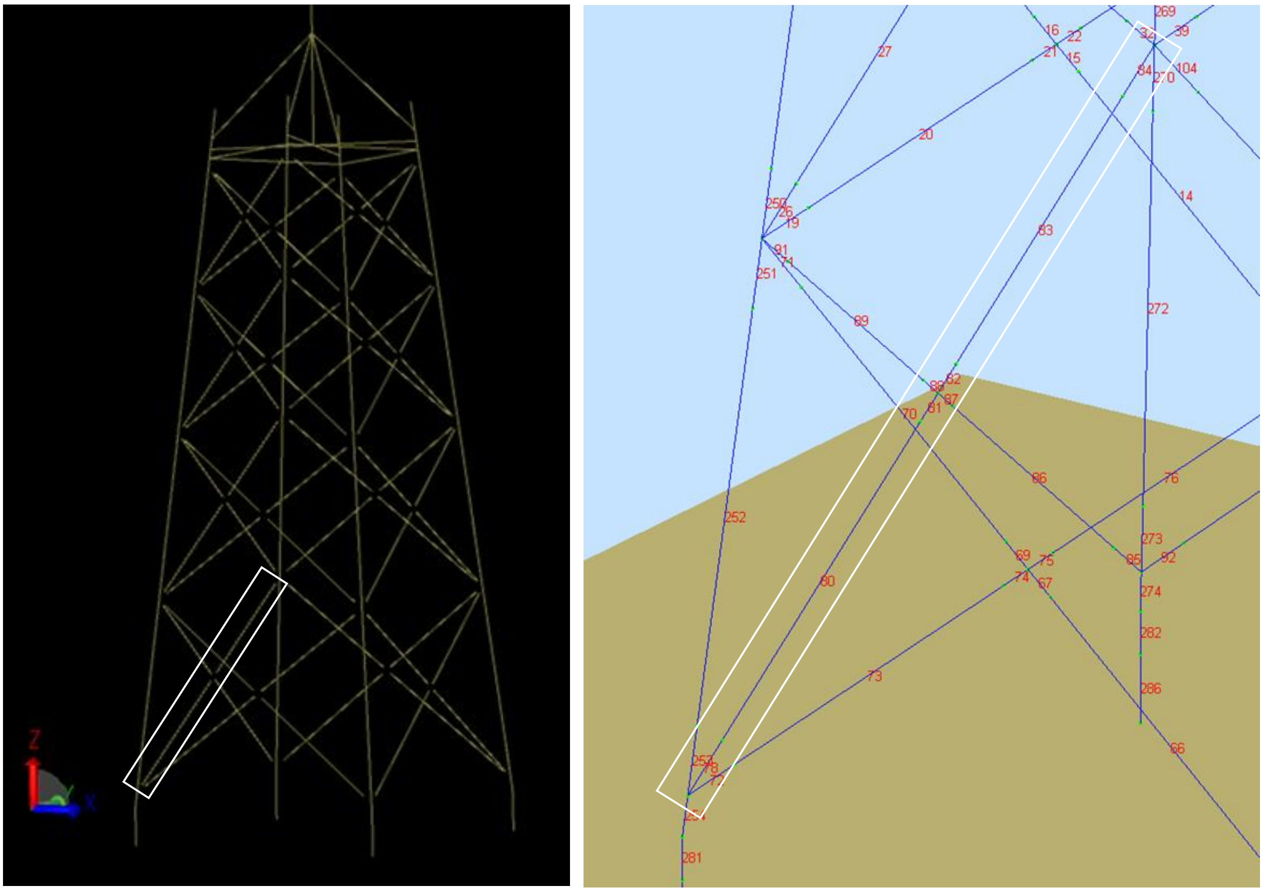


Figure 5-1 – Location of selected members for force / moment comparisons, left-hand image shows the Sesam model and right-hand image shows the imported Bladed model with Bladed member numbers for the selected beam [mbrs: 78,80,81,82,83,84]

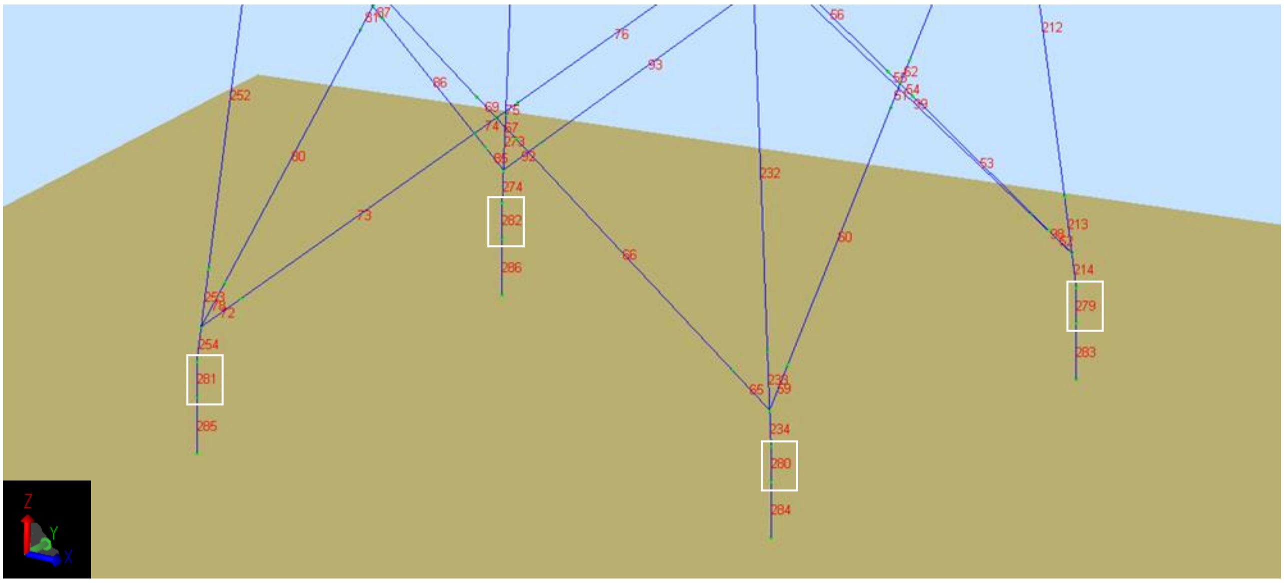


Figure 5-2 – Bladed model showing numbering of the selected pile cap members [mbrs: 279, 280, 281, 282]

5.2 Bladed / Sesam load components

Figure 5-3 below shows the global and local coordinate frames for the offset jacket model in Sesam GeniE. The local coordinate systems for the Bladed model follow an equivalent alignment to the Sesam model, but with different axis labels as described in Table 5-1. The sign convention in Bladed for two of the axes are different to Sesam, as described in APPENDIX A.

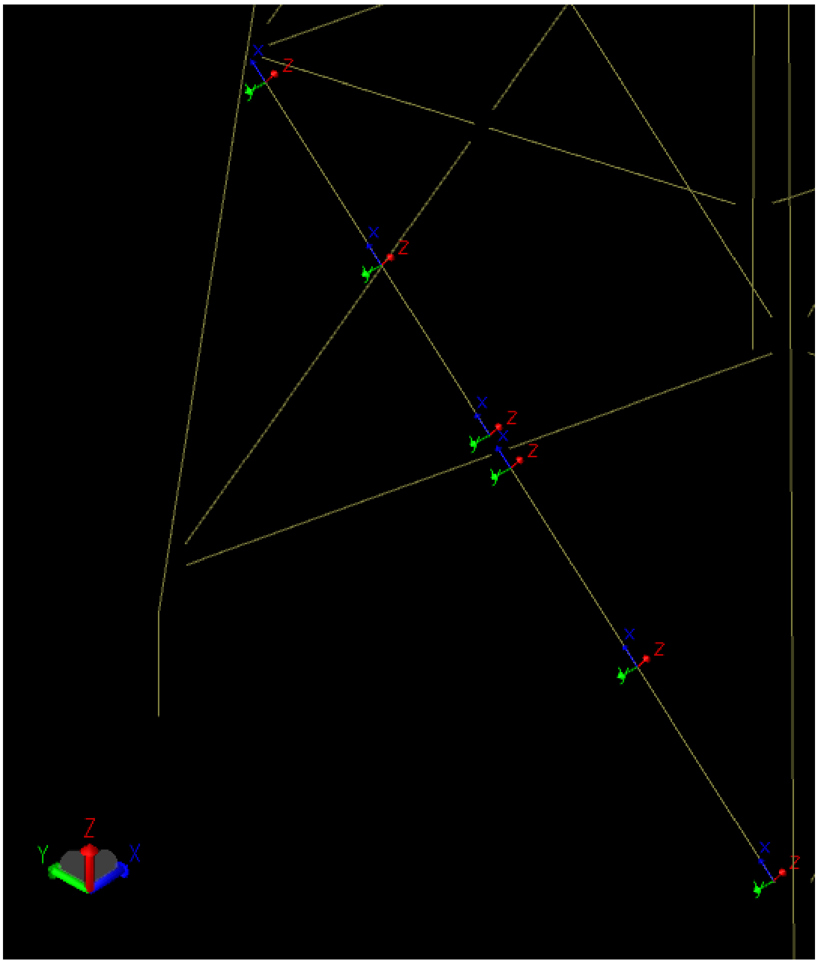


Figure 5-3 – Global and local member coordinates for the selected beam member of the jacket model in Sesam, x=red, y=green, z=blue. Note that the coordinate axes are positioned at non-offset node positions.

Table 5-1 – Equivalent load labelling for Bladed and Sesam, referring to local member / beam coordinates

Bladed label	Fx	Fy	Fz	Mx	My	Mz
Sesam label	Nxx	Nxy *	Nxz	Mxx	Mxy *	Mxz

*Note: For the results presented in this document, the sign of the Sesam xy load components has been manually inverted so they are equivalent to the Bladed y load component, see further details in APPENDIX A.

5.3 Results Summary

Both the Bladed and Sesam models were run with a constant 4m/s current that is uniform throughout the water column. In Genie this was run as a static load case, in Bladed this was run as a short time history run.

The figures in the following two sub-sections show comparisons between Bladed and Sesam for positions along a diagonal brace member (see Figure 5-1) and also at each of the four pile cap positions (see Figure 5-2), both with and without LJFs included. In each case results are compared for components of beam torsion, bending moment, axial force and shear force. Visually the overlapping lines for the Sesam and Bladed results indicate an excellent match for each of the cases. The figures also include vertical bars to illustrate percentage difference between the Bladed and Sesam results at each beam location. In general, these percentage ‘error bars’ confirm an excellent match in the region of 0.1% to 0.5%. In some cases, much larger percentage errors are highlighted, however upon closer inspection it is found that these only occur at locations where the absolute value of results are very small. Such errors can be neglected (i.e. locations with very low absolute load levels are highly unlikely to be significant for ULS or FLS assessment of the jacket design).

The Sesam and Bladed results for pile cap reactions are shown to match within 0.1%, both if LJFs are included or excluded.

5.3.1 Submerged diagonal brace (mbrs 78-84)

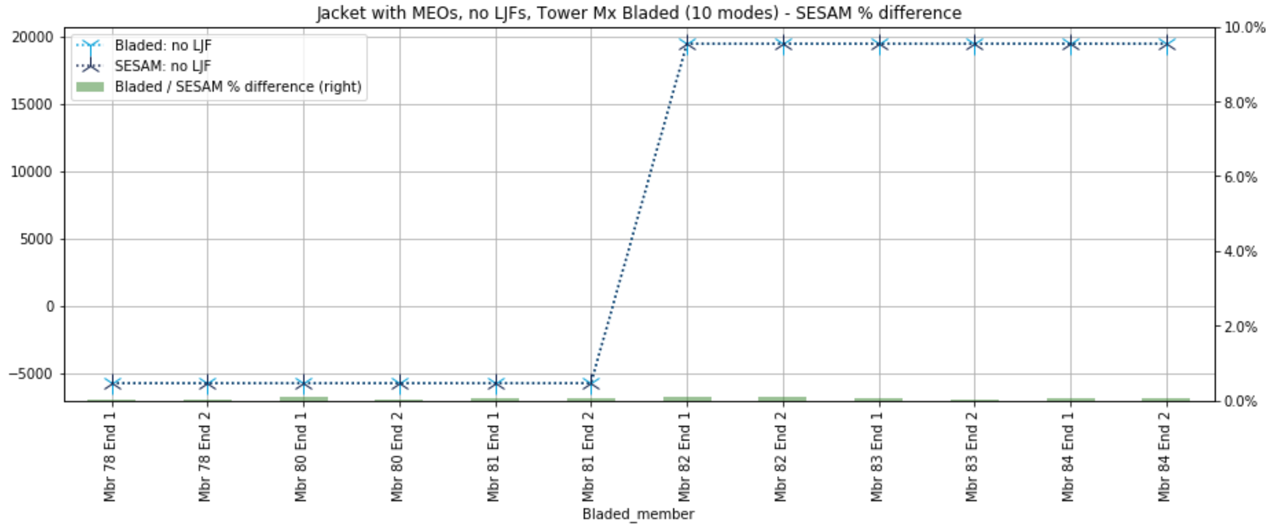


Figure 5-4 – Torsion moment Mx for Bladed and Sesam without LJFs

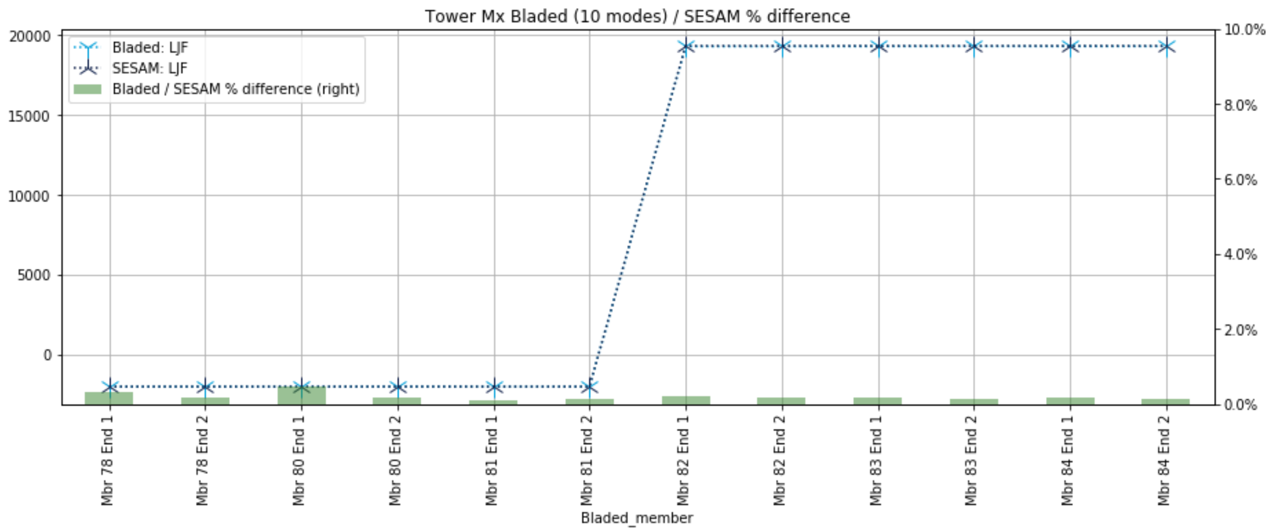


Figure 5-5 – Torsion moment Mx for Bladed and Sesam with LJFs

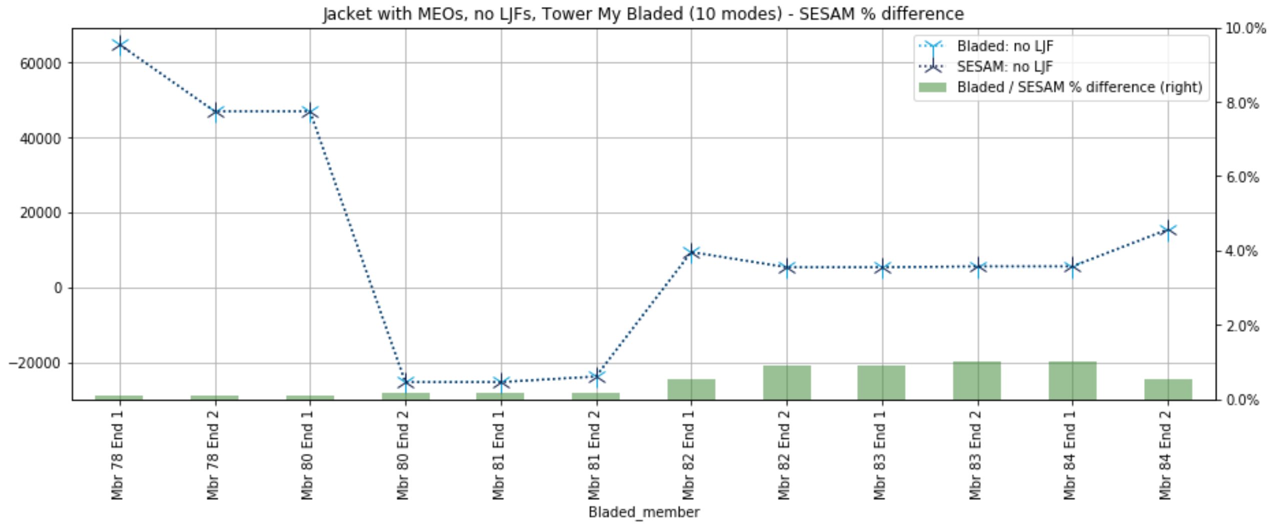


Figure 5-6 – Bending moment My for Bladed and Sesam <u>without LJFs</u>

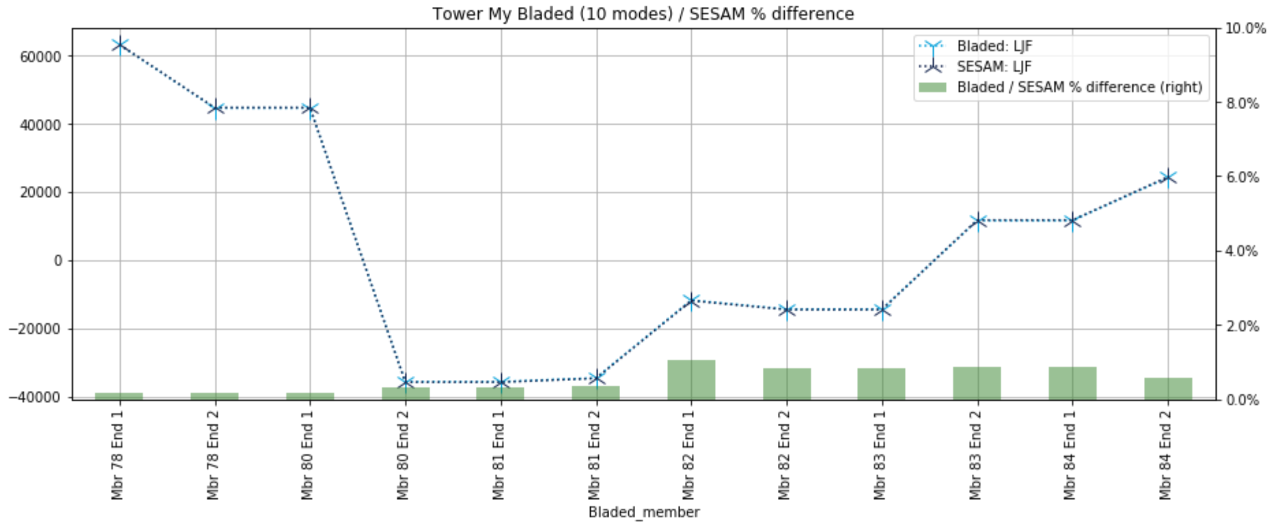


Figure 5-7 – Bending moment My for Bladed and Sesam <u>with LJFs</u>

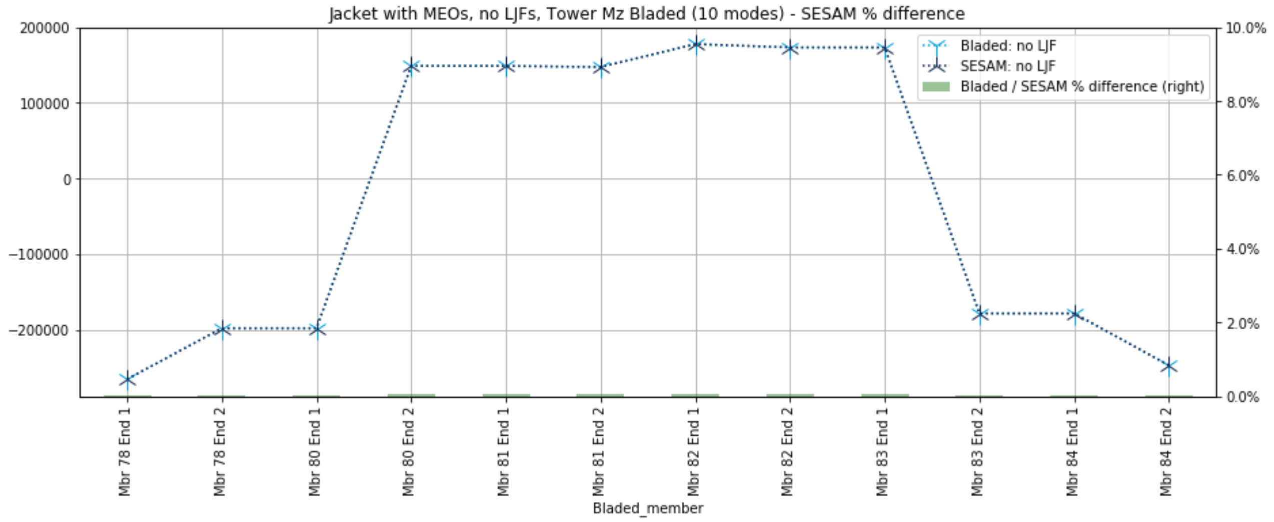


Figure 5-8 – Bending moment Mz for Bladed and Sesam without LJFs

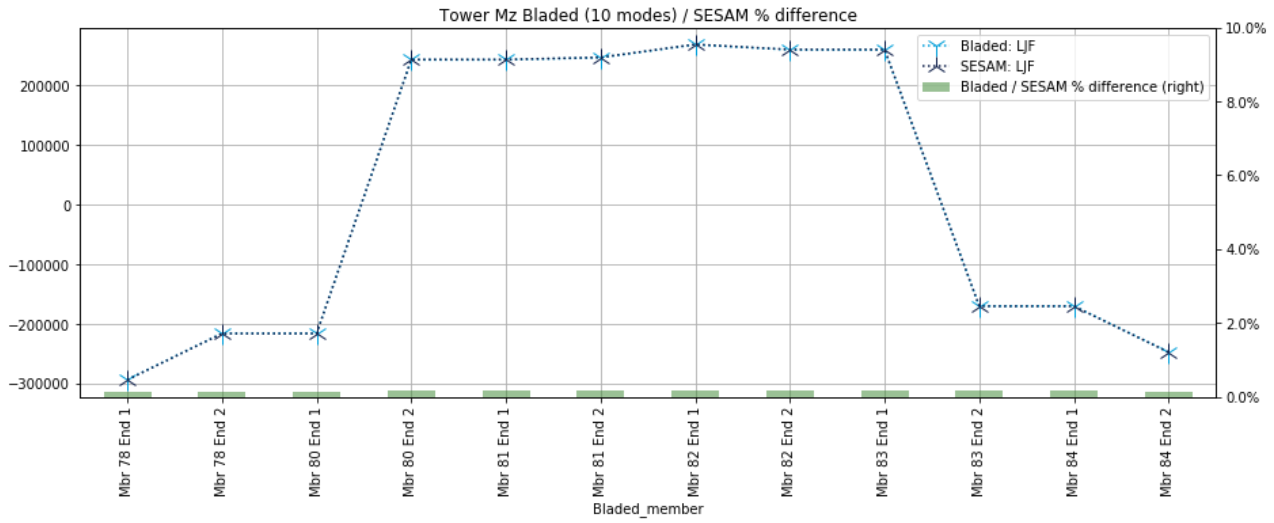


Figure 5-9 – Bending moment Mz for Bladed and Sesam with LJFs

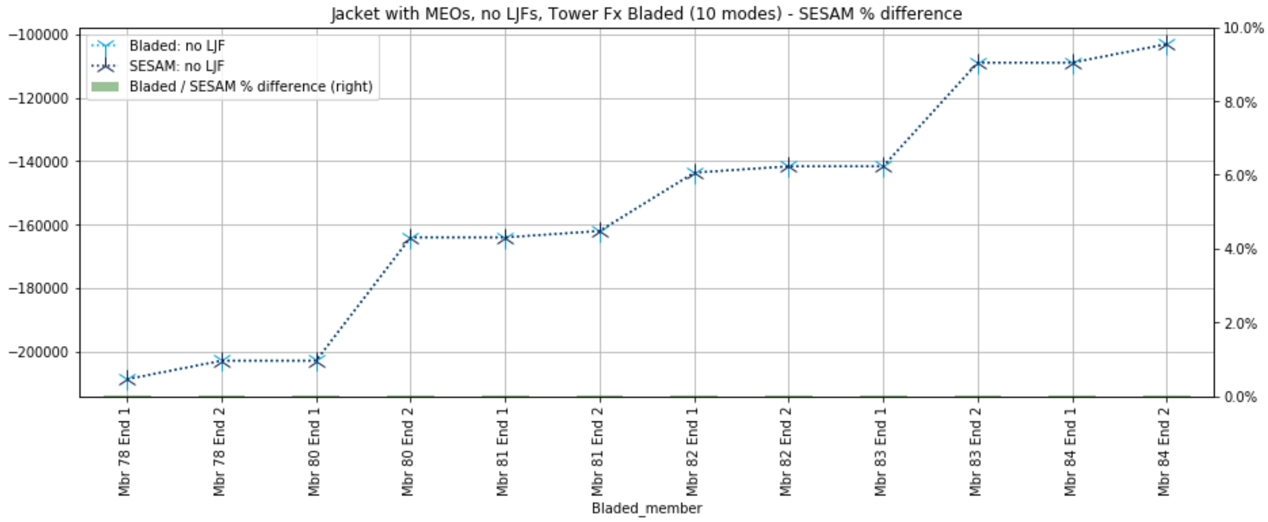


Figure 5-10 – Axial force Fx for Bladed and Sesam without LJFs

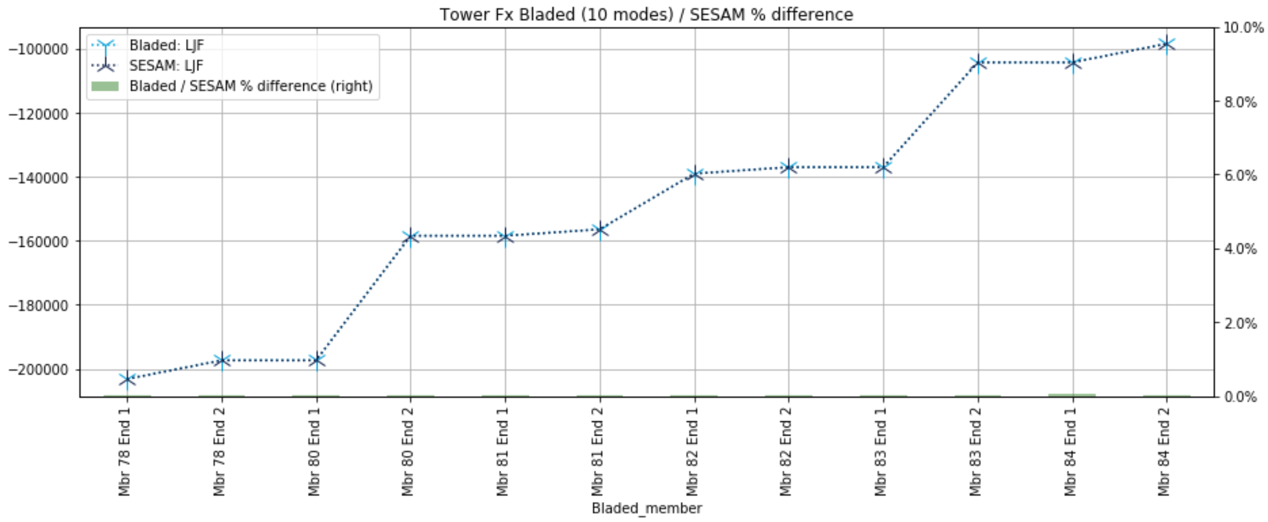


Figure 5-11 – Axial force Fx for Bladed and Sesam with LJFs

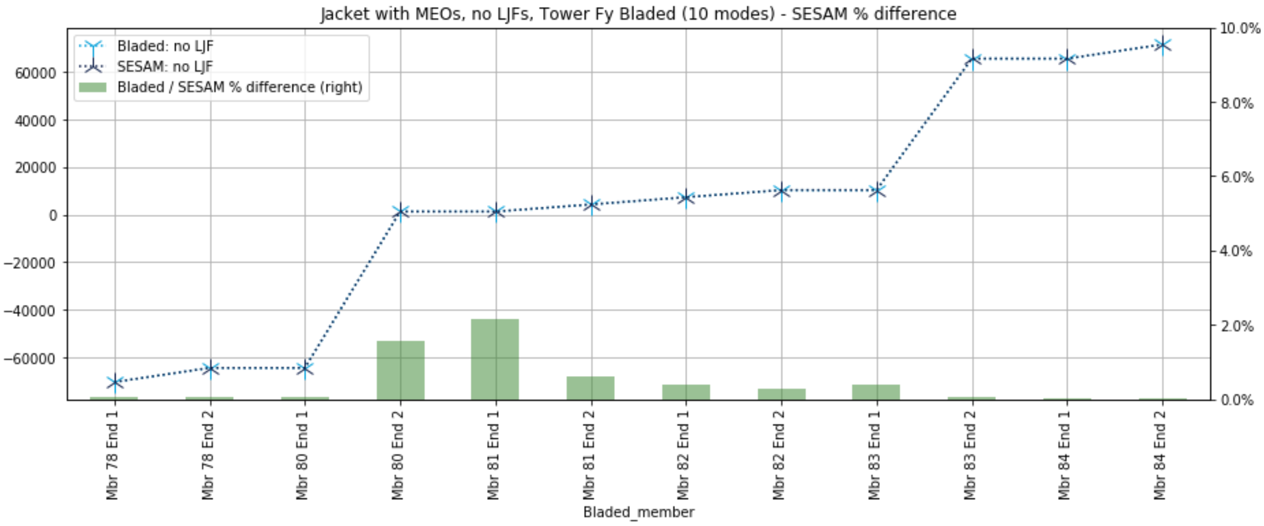


Figure 5-12 – Shear force Fy for Bladed and Sesam <u>without LJFs</u>

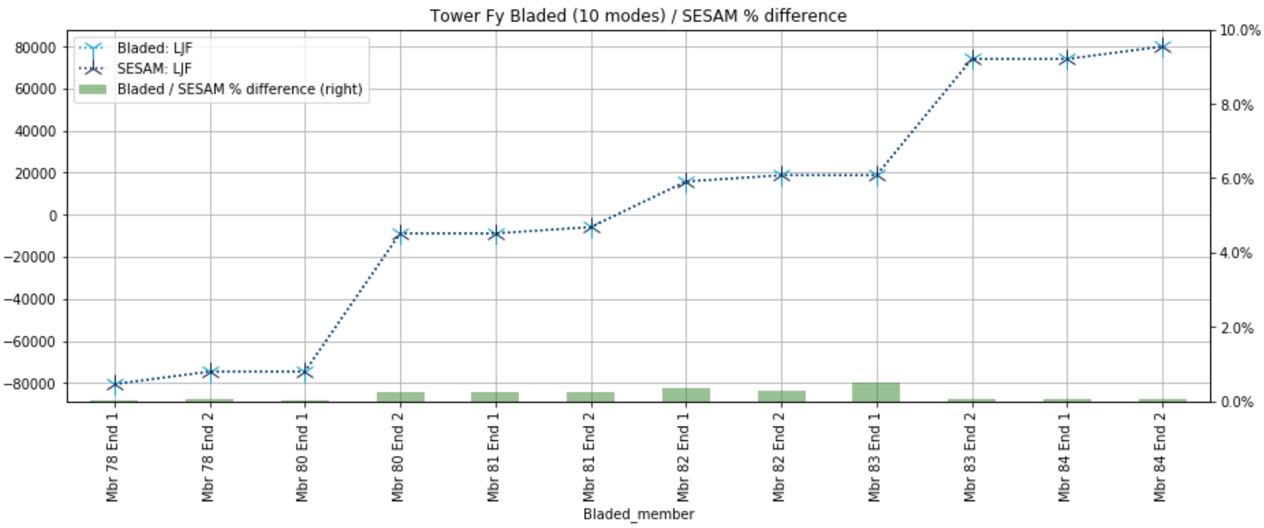


Figure 5-13 – Shear force Fy for Bladed and Sesam <u>with LJFs</u>

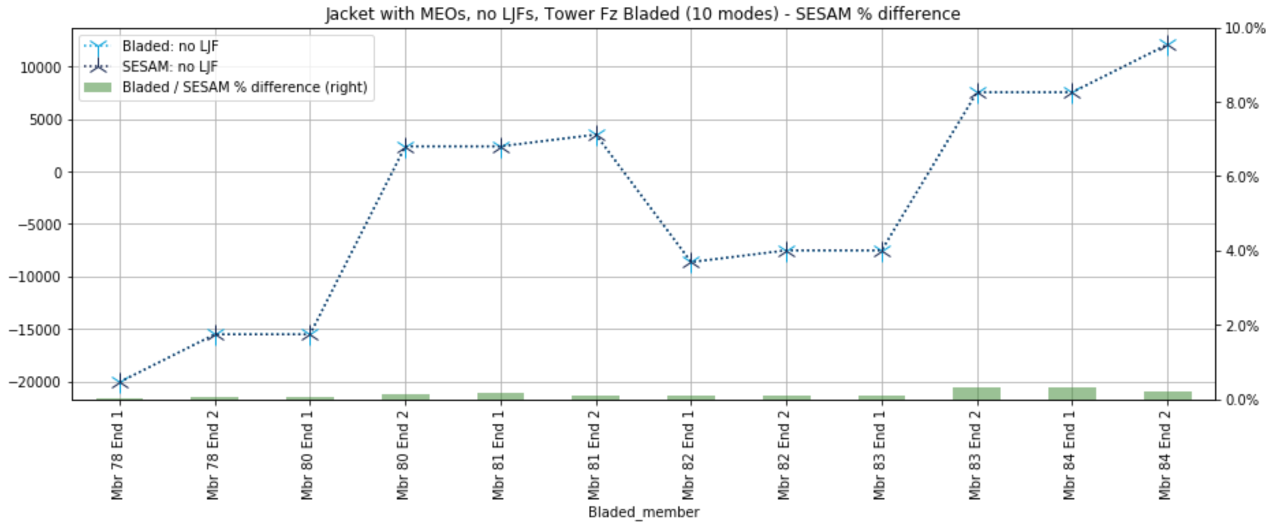


Figure 5-14 – Shear force Fz for Bladed and Sesam without LJFs

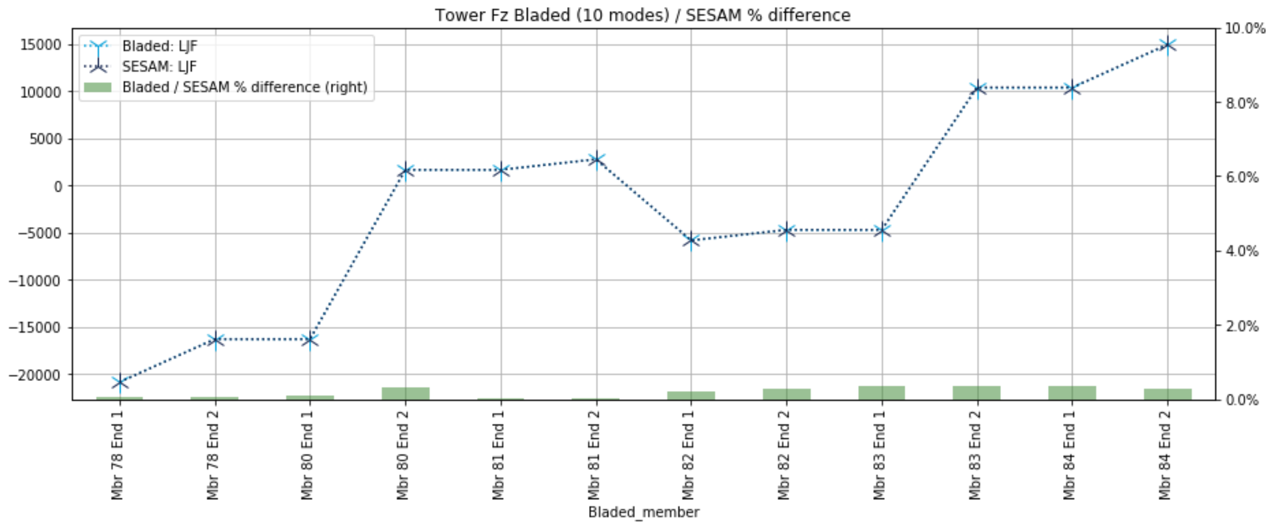


Figure 5-15 – Shear force Fz for Bladed and Sesam Sesam with LJFs

5.3.2 Pile cap reactions (mbrs 279, 280, 281, 282)

Table 5-2 – Comparison of Sesam and Bladed pile cap reactions with and without LJFs

		No-LJF			LJF			Change in global reactions due to LJFs	
	Component (global axes)	Sesam (N or Nm)	Bladed (N or Nm)	% difference (Sesam-Bladed)	Sesam (N or Nm)	Bladed (N or Nm)	% difference (Sesam-Bladed)	Sesam	Bladed
Mbr 279 End 1	Fx	1.33E+06	1.33E+06	**-0.06%**	1.32E+06	1.32E+06	**-0.07%**	0.49%	0.48%
	Fy	4.98E+05	4.98E+05	**-0.01%**	4.92E+05	4.92E+05	**-0.01%**	1.37%	1.38%
	Fz	-5.49E+06	-5.49E+06	**0.00%**	-5.48E+06	-5.48E+06	**0.00%**	0.12%	0.12%
	Mx	-4.93E+05	-4.93E+05	**0.01%**	-4.85E+05	-4.85E+05	**0.02%**	1.58%	1.60%
	My	2.54E+06	2.54E+06	**0.00%**	2.59E+06	2.59E+06	**0.01%**	-1.94%	-1.94%
	Mz	4.16E+05	4.16E+05	**0.03%**	4.64E+05	4.64E+05	**0.08%**	-10.42%	-10.37%
Mbr 280 End 1	Fx	1.33E+06	1.33E+06	**-0.06%**	1.31E+06	1.31E+06	**-0.08%**	1.86%	1.85%
	Fy	-4.98E+05	-4.98E+05	**-0.01%**	-4.92E+05	-4.92E+05	**-0.01%**	1.21%	1.21%
	Fz	-5.49E+06	-5.49E+06	**0.00%**	-5.48E+06	-5.48E+06	**0.00%**	0.08%	0.08%
	Mx	4.93E+05	4.93E+05	**0.01%**	4.85E+05	4.85E+05	**0.02%**	1.64%	1.65%
	My	2.55E+06	2.55E+06	**0.00%**	2.55E+06	2.55E+06	**0.00%**	-0.30%	-0.30%
	Mz	-4.14E+05	-4.13E+05	**0.03%**	-4.21E+05	-4.21E+05	**0.06%**	-1.75%	-1.71%
Mbr 281 End 1	Fx	6.76E+05	6.76E+05	**-0.04%**	7.01E+05	7.02E+05	**-0.05%**	-3.62%	-3.63%
	Fy	-1.55E+05	-1.55E+05	**0.01%**	-1.49E+05	-1.49E+05	**0.02%**	3.95%	3.96%
	Fz	-1.76E+06	-1.76E+06	**0.01%**	-1.77E+06	-1.77E+06	**0.01%**	-0.26%	-0.26%
	Mx	8.76E+04	8.76E+04	**-0.01%**	6.38E+04	6.38E+04	**-0.02%**	37.25%	37.23%
	My	1.96E+06	1.96E+06	**0.00%**	2.07E+06	2.07E+06	**0.00%**	-5.29%	-5.29%
	Mz	-4.15E+05	-4.15E+05	**0.03%**	-4.73E+05	-4.72E+05	**0.09%**	-12.15%	-12.09%
Mbr 282 End 1	Fx	6.77E+05	6.77E+05	**-0.04%**	6.82E+05	6.82E+05	**-0.05%**	-0.77%	-0.78%
	Fy	1.55E+05	1.55E+05	**0.01%**	1.50E+05	1.50E+05	**0.01%**	3.38%	3.39%
	Fz	-1.76E+06	-1.76E+06	**0.01%**	-1.77E+06	-1.77E+06	**0.00%**	-0.34%	-0.34%
	Mx	-8.77E+04	-8.77E+04	**-0.02%**	-7.06E+04	-7.06E+04	**-0.05%**	24.30%	24.27%
	My	1.97E+06	1.97E+06	**0.00%**	2.03E+06	2.03E+06	**0.00%**	-3.25%	-3.24%
	Mz	4.13E+05	4.13E+05	**0.03%**	4.22E+05	4.22E+05	**0.08%**	-2.12%	-2.07%

6 CONCLUSIONS

A full jacket test model is used to examine the result differences in Bladed and Sesam when the Local Joint Flexibility (LJF) feature is used. Separate analyses were run in both Bladed and Sesam to investigate result differences for the cases of static loading (uniform current), and computation of modal frequencies. The test models were first created in Sesam and then converted to Bladed format using Sesam Wind Manager, before defining equivalent analysis settings in each case.

The outcomes of this study are summarised as follows:

- LJFs are demonstrated to have a very small influence on global modal frequencies and a significant influence on higher order modes. This is expected because higher modes are associated with local deflections of individual brace members whose relative stiffness may be significantly influenced by the presence of LJFs.
- The Bladed and Sesam computed modal frequencies show very good agreement for the first 50 modes, both with and without LJFs. The difference between Sesam and Bladed results for the first two global modal frequencies is less than 0.1% when LJFs are included in the jacket model. Differences in Bladed-Sesam results for higher modes (up to 50 modes) are generally below 0.5% difference.
- Comparisons of member force/moment calculations under static loading comparisons show very good and similar levels of agreement between Bladed and Sesam results both with and without LJFs included. The difference in computed out-of-plane bending moment between Sesam and Bladed at the location of maximum bending moment for a selected brace member is approximately 0.3% for the model with LJFs. Reactions at the pile caps are less than 0.1% different.

Based on the above summary, it is shown that Bladed and Sesam have good agreement of results in models with and without Local Joint Flexibilities (LJFs), provided that model settings of geometric stiffness, Morison, buoyancy and damping are aligned. The results provide confidence that the LJF feature has similar effects within the Bladed and Sesam analyses and it is appropriate to use the member-end-offset feature within the Bladed/Sesam integrated design workflow.

7 REFERENCES

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/3/ DNV GL, Verification report of Sesam’s Bladed interface, 2016-0866, Rev. 2, 2019-03-13

/4/ DNV, Bladed User manual, version 4.13

/5/ DNV GL, Xtract User manual, version 5.4

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APPENDIX A BLADED / SESAM LOAD OUTPUTS

Figure A-1 shows the definitions of forces from the Bladed /4/ and Xtract manual /5/, showing that Fy is the inverse of Nxy and My is the inverse of Mxy.

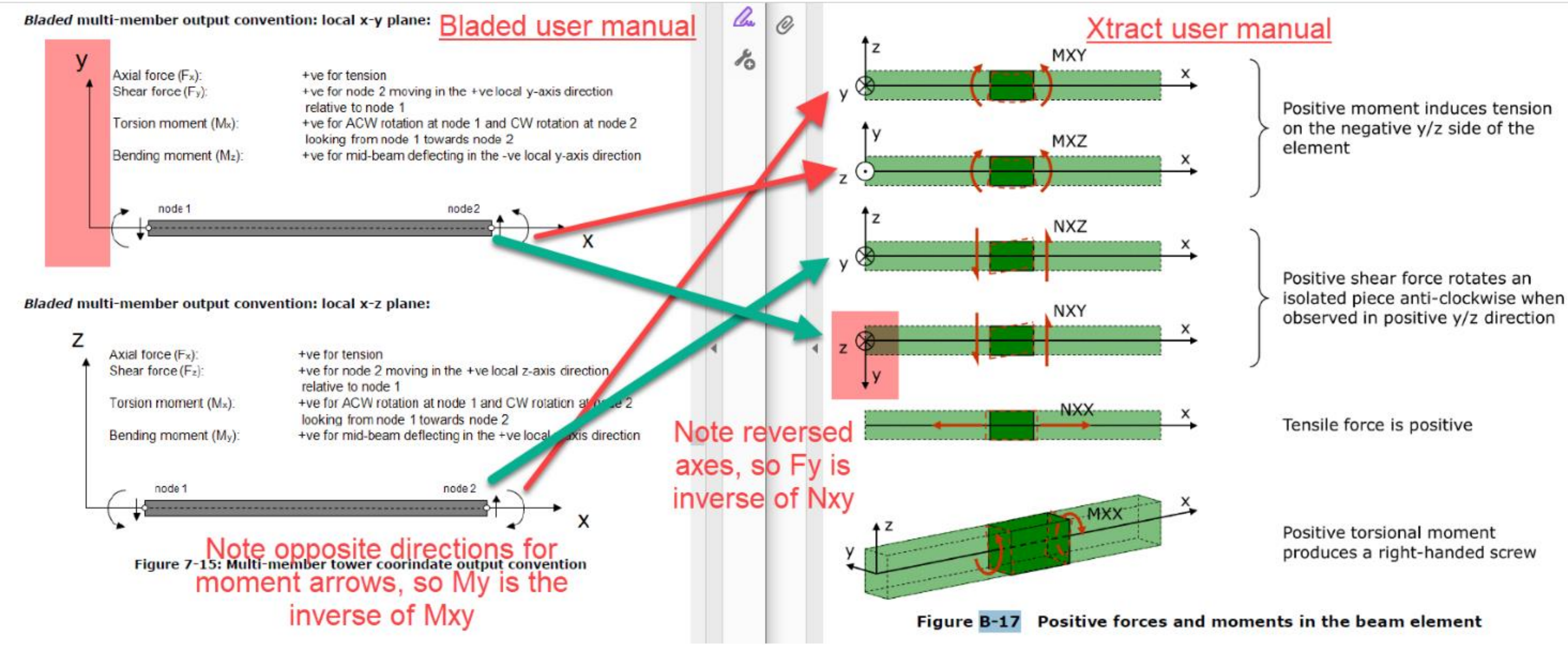

Figure A-1 - Bladed and Xtract (Sesam) coordinate systems for outputs

To summarise:

- Axial force:
    - Bladed (Fx): tension is positive
    - Sesam (NXX): tension is positive
    - Matches
- Shear force
    - In local x-y plane:
        - Bladed (Fy): positive for node 2 moving in the positive local y-axis direction relative to node 1
        - Sesam (NXY): positive shear force rotates an isolated piece anti-clockwise when observed in positive z direction
        - Not matching, the positive direction is opposite.
    - In local x-z plane:
        - Bladed (Fz): positive for node 2 moving in the positive local z-axis direction relative to node 1
        - Sesam (NXZ): positive shear force rotates an isolated piece anti-clockwise when observed in positive y direction
        - Matches
- Torsion moment:
    - Bladed (Mx): positive for anti-clockwise rotation at node 1 and clockwise rotation at node 2 looking from node 1 towards node 2.
    - Sesam (MXX): positive torsional moment produces a right-handed screw
    - Matches
- Bending moment:
    - In local x-y plane:
        - Bladed (Mz): positive for mid-beam deflecting in the negative local y-axis direction
        - Sesam (MXZ): positive moment induces tension on the negative y side of the element
        - Matches
    - In local x-z plane:
        - Bladed (My): positive for mid-beam deflecting in the positive local z-axis direction
        - Sesam (MXY): positive moment induces tension on the negative z side of the element
        - Not matching, the positive direction is opposite.

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