Verification of Bladed against SACS for use in Integrated Offshore Support Structure Design

Report No.: 110052-UKBR-T-18, Rev. A
Date: 30/09/2014

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1 SUMMARY

In 2012 a link was developed between Bladed, a widely-used aeroelastic wind turbine design tool, and SACS, one of the leading offshore structural design codes. For offshore structural design Bladed is able to calculate simultaneous wind and wave loading on the combined wind turbine and support structure in the time domain. This integrated design approach ensures that the resulting loads on the foundation take full account of the complex interactions between the turbine and support structure. The Bladed-SACS link allows foundation load time histories from Bladed to be used directly in SACS for fatigue (FLS) and extreme (ULS) code checking, enabling strength checks to be performed on complex jacket support structures in a streamlined and efficient way. Previous studies have shown that significant lifetime cost of energy savings for offshore wind are possible when the fully integrated design approach is exploited in this way.

To give the industry confidence in this integrated design approach it is important to demonstrate that Bladed and SACS are aligned in their wave loading calculation methods. DNV GL and Keystone Engineering collaborated to compare wave loading results for a representative jacket structure from Bladed and SACS. First, the structural model is matched as closely as possible between the two codes in terms of geometry, mass and stiffness and the resulting natural frequencies are compared. Identical time domain simulations are then performed in both codes including dynamic wave loading from irregular and constrained waves. The results show good agreement between the two codes in terms of extreme and fatigue loading, demonstrating that the wave load and member load calculations in Bladed and SACS are consistent with each other.

This comparison study was originally presented at the American Wind Energy Association (AWEA) Offshore Wind Power 2014 Conference in Atlantic City.

2 INTRODUCTION: INTEGRATED DESIGN

Offshore wind turbine support structure designers typically employ a "sequential" approach to the design, as illustrated in Figure 2-1, where the wind turbine and offshore support structure are modelled in separate design tools. The sequential approach may not fully account for the complex interactions between the turbine and the support structure. Furthermore, the designer's workflow is inefficient as repeated data exchange is required between the different design codes.

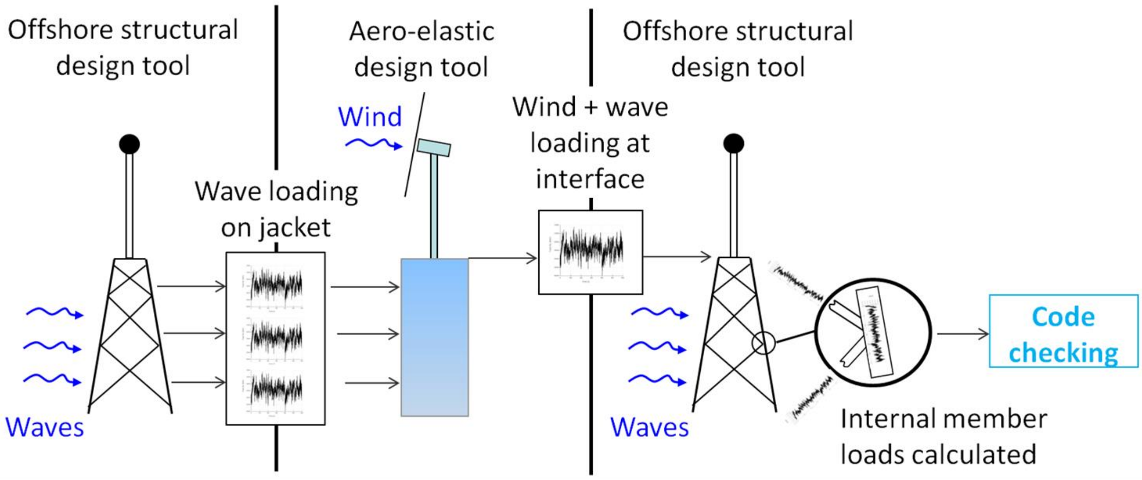

Figure 2-1: Sequential support structure design schematic

Alternatively an "integrated" design approach may be employed, as illustrated in Figure 2-2, where the wind turbine and support structure are modelled in a single aero-hydro-elastic software package. The structural dynamics of the whole structure are coupled, and wind and wave loads applied simultaneously. This means that aerodynamic and hydrodynamic damping can be properly accounted for, resulting in a more efficient structural design. A dedicated offshore support structure code is only required at the end of each design iteration to perform FLS and ULS code checking on the joints and members. To this end a link has been developed between Bladed, a widely-used aero-hydro-elastic wind turbine design tool, and SACS, a widely-used offshore structural design tool. The Bladed-SACS link enables the simultaneous wind and wave loading to be calculated on the complete structure in Bladed and the resulting foundation load time histories to then be post-processed directly in SACS. Previous studies [1] have shown that significant lifetime cost of energy savings are possible when the fully integrated design approach is exploited in this way.

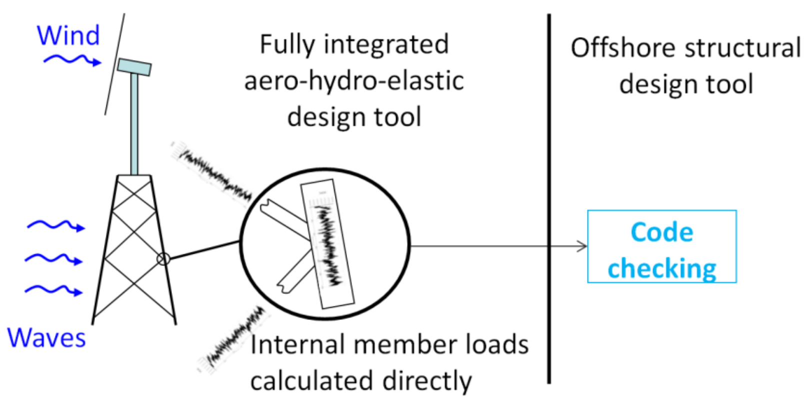

Figure 2-2: Integrated support structure and turbine design

To give the industry confidence in moving towards an integrated design approach, it must be demonstrated that integrated design tools like Bladed can perform equivalent support structure analysis to that currently undertaken in offshore structural design tools like SACS. Specifically, the wave loading and resulting member internal loading in Bladed and SACS must be shown to be equivalent.

3 METHOD: DYNAMIC MODELLING

The aim of the study is to show that Bladed and SACS report similar member loads when wave loading is applied to a jacket support structure. This section describes the definition of the turbine model and environment used to carry out the code comparison.

3.1 Turbine Definition

Models of a typical wind turbine jacket and tower were built in Bladed and SACS with 31m water depth. The rotor, nacelle and associated aerodynamic loading were excluded in order to provide a direct comparison of wave loading between the two codes. The structure used is shown in Figure 3-1. Three locations in the jacket were chosen for load comparison as illustrated.

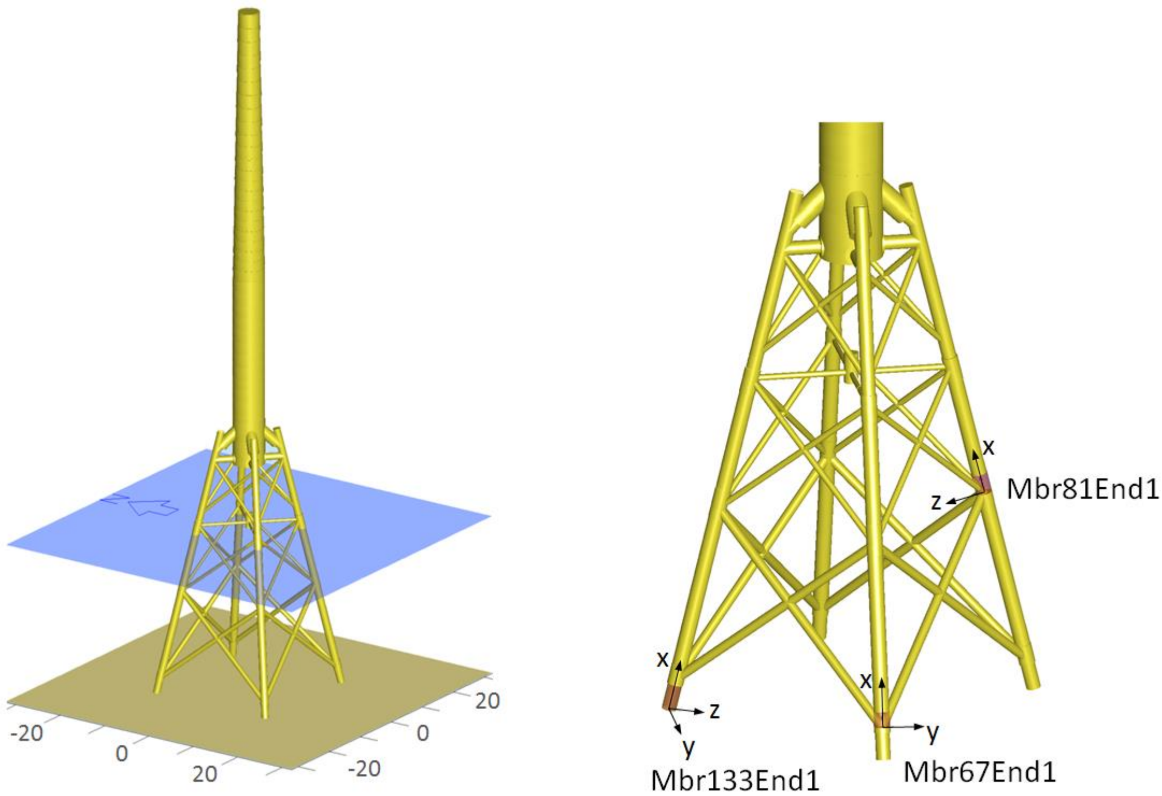

Figure 3-1: Support structure used for Bladed and SACS analysis

Both structures were defined using beam elements including shear deflection. The foundations were modelled as rigid at the mudline. Morison loading coefficients of C_D = 1, C_M = 2 were assumed for all members. Brace members were sealed (full of air). Leg members were flooded up to mean sea level of 31m. Marine growth thickness was set to zero for all members.

Structural vibration modes up to 7.5Hz were calculated for both models, and a damping of 2% specified for each mode. A comparison of the first 20 vibration modes calculated in SACS and Bladed is shown in Table 3-1. Generally a good agreement is seen in the modal frequency predictions.

MODE	SACS normal node frequency (Hz)	Bladed coupled mode frequency (Hz)
1	0.821	0.820
2	0.821	0.820
3	2.700	2.706
4	2.700	2.712
5	4.005	3.811
6	4.308	4.103
7	4.308	4.154
8	5.042	4.803
9	5.155	5.029
10	5.158	5.046
11	5.727	5.232
12	5.995	5.566
13	6.053	5.605
14	6.157	5.656
15	6.283	5.745
16	6.580	6.391
17	7.208	6.618
18	7.505	6.789
19	7.536	7.008
20	7.539	7.297

Table 3-1: Modal frequencies calculated in SACS and Bladed

3.2 Environment Definition

Fatigue and extreme sea state conditions were defined and are described in this section.

3.2.1 Extreme sea state

For the extreme simulation, a 60-second irregular sea state was defined with the following properties

- Hs = 6.83 m
- Tp = 10 s
- Peakedness = 1 (Pierson–Moskowitz)

A single linear New Wave "constrained" wave was also included in the wave history, with the following properties

- Constrained wave height = 12.7m
- Time of wave crest in simulation = 30s

The resulting sea state is shown in Figure 3-2.

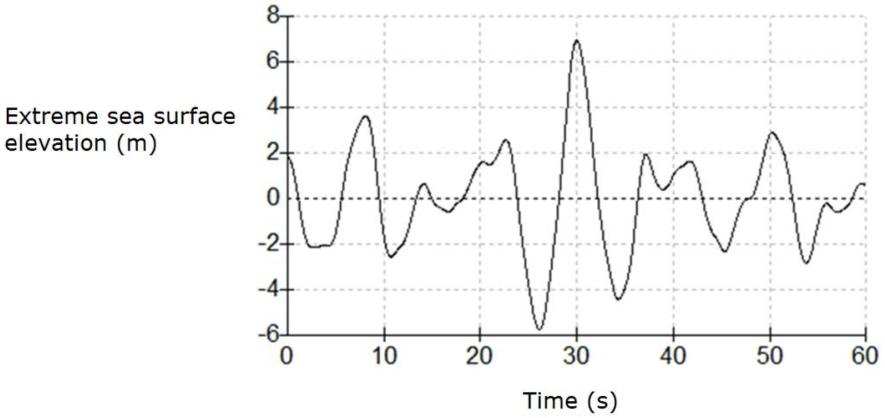

Figure 3-2: Extreme sea surface elevation

The waves were assumed to be approaching from North.

3.2.2 Fatigue sea state

For the fatigue sea state, a 600-second irregular sea state was defined with the following properties

- Hs = 5 m
- Tp = 10 s
- Peakedness = 1 (Pierson–Moskowitz)

A sample of the resulting sea state is shown in Figure 3-2.

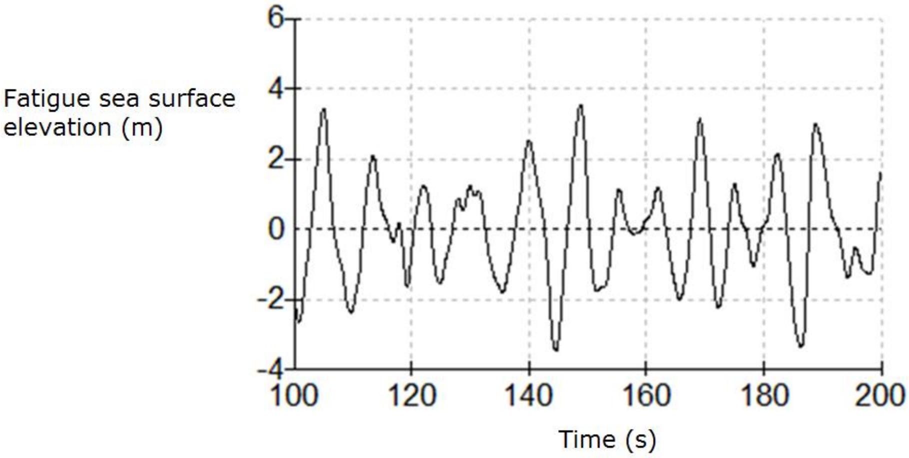

Figure 3-3: Fatigue sea surface elevation

The waves were assumed to be approaching from North.

3.3 Simulation description

Two time domain simulations were carried out in SACS and Bladed: one for the fatigue sea state and another for the extreme sea state.

4 RESULTS: COMPARISON OF SACS AND BLADED

Extreme loading, fatigue loading and time histories from Bladed and SACS are presented and compared in this section.

4.1 Extreme Loading

Extreme loading time history comparisons are presented for the three specified locations in the jacket.

4.1.1 Extreme loading: Member 67

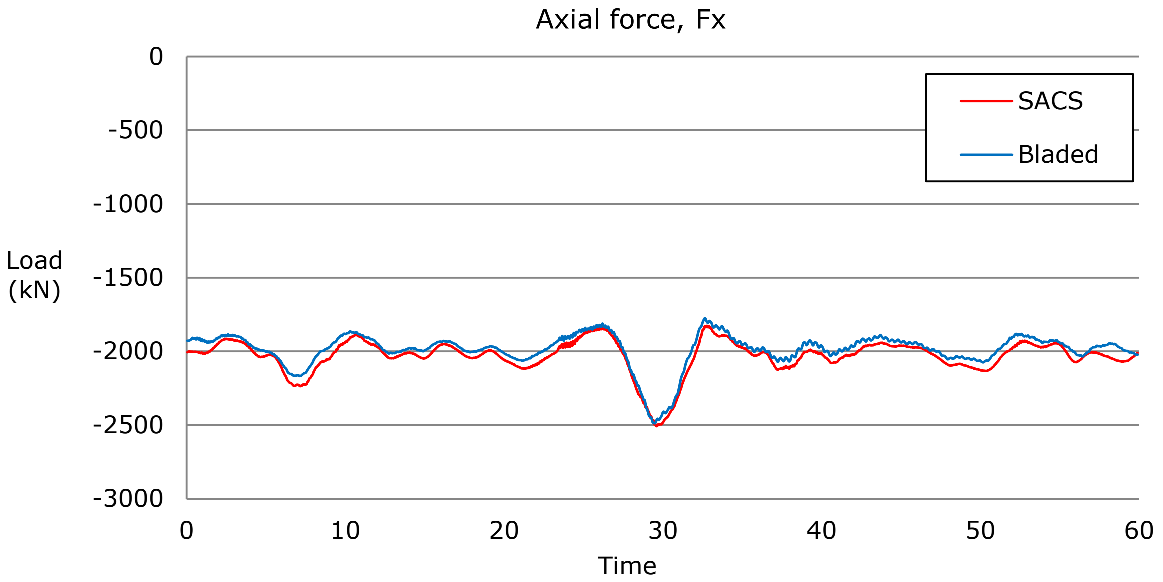

Figure 4-1: Extreme sea state, axial force in Member 67

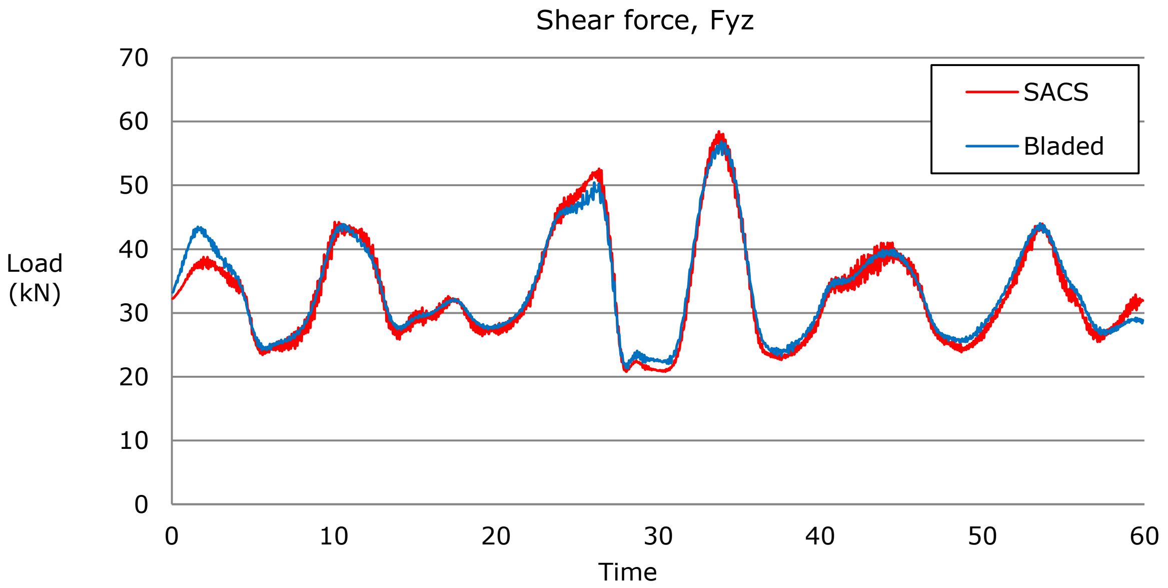

Figure 4-2: Extreme sea state, shear force in Member 67

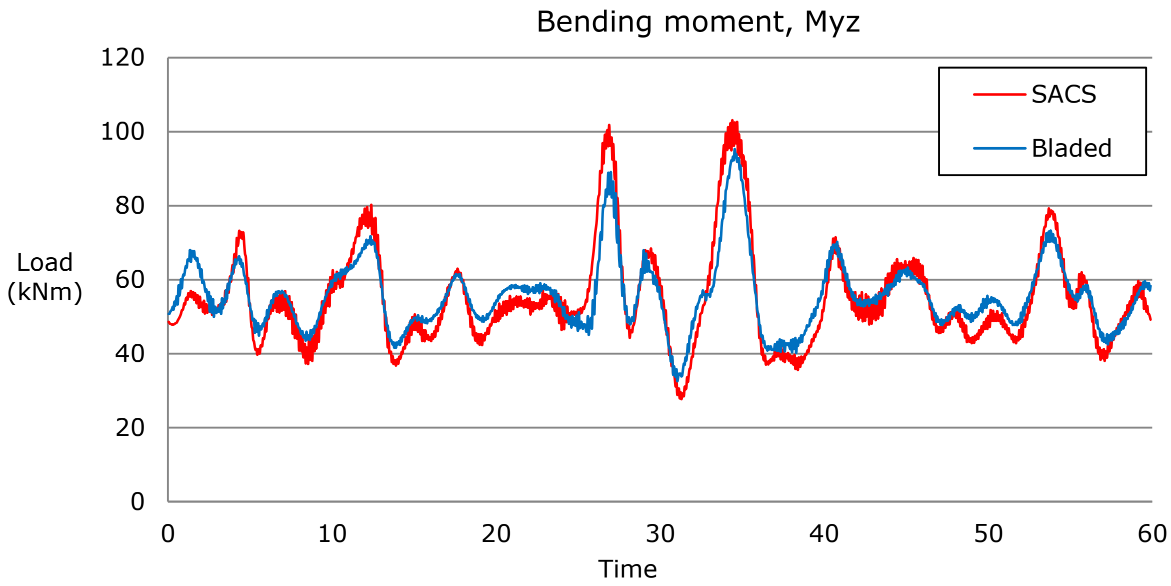

Figure 4-3: Extreme sea state, bending moment in Member 67

4.1.2 Extreme loading: Member 81

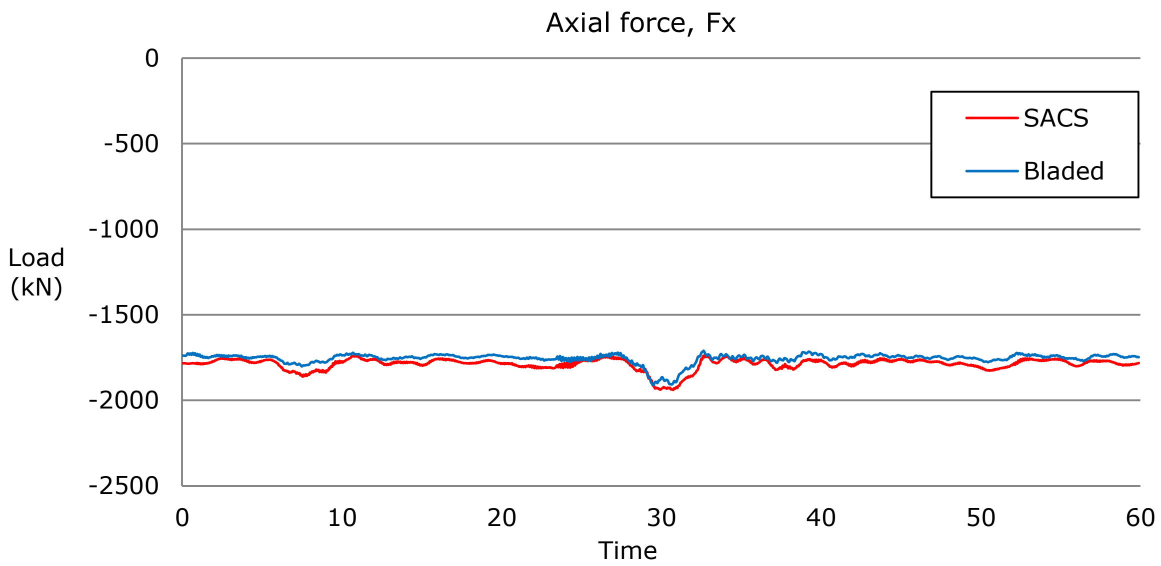

Figure 4-4: Extreme sea state, axial force in Member 81

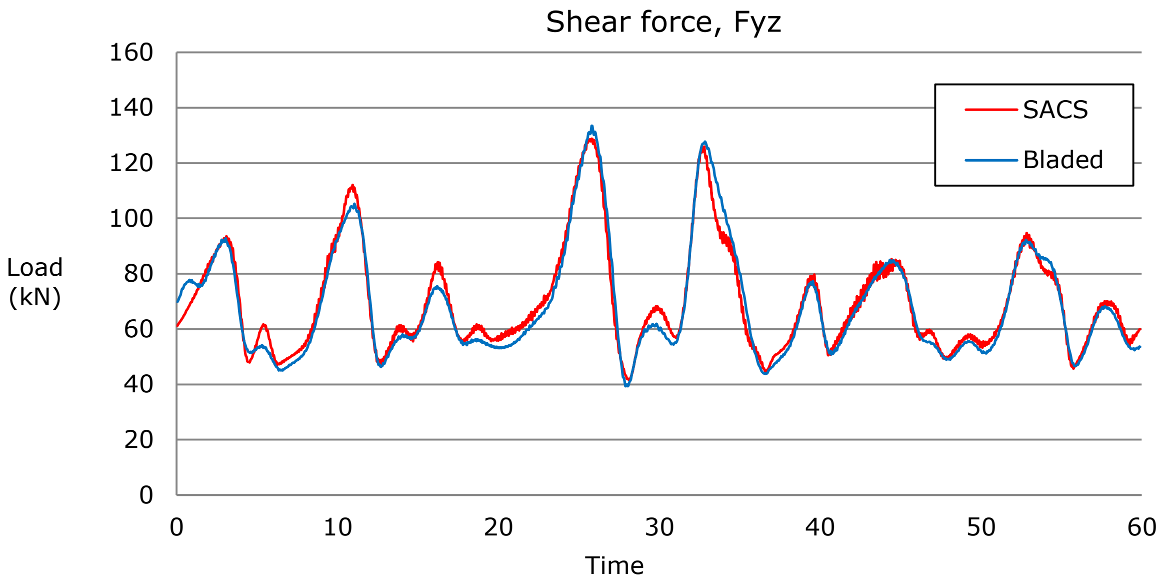

Figure 4-5: Extreme sea state, shear force in Member 81

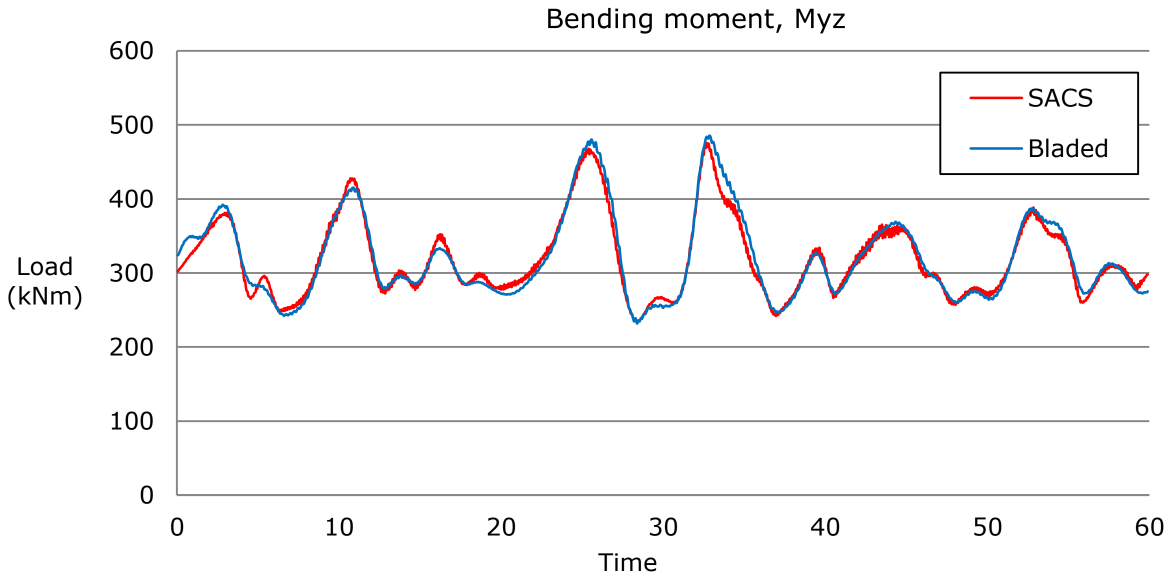

Figure 4-6: Extreme sea state, bending moment in Member 81

4.1.3 Extreme loading: Member 133

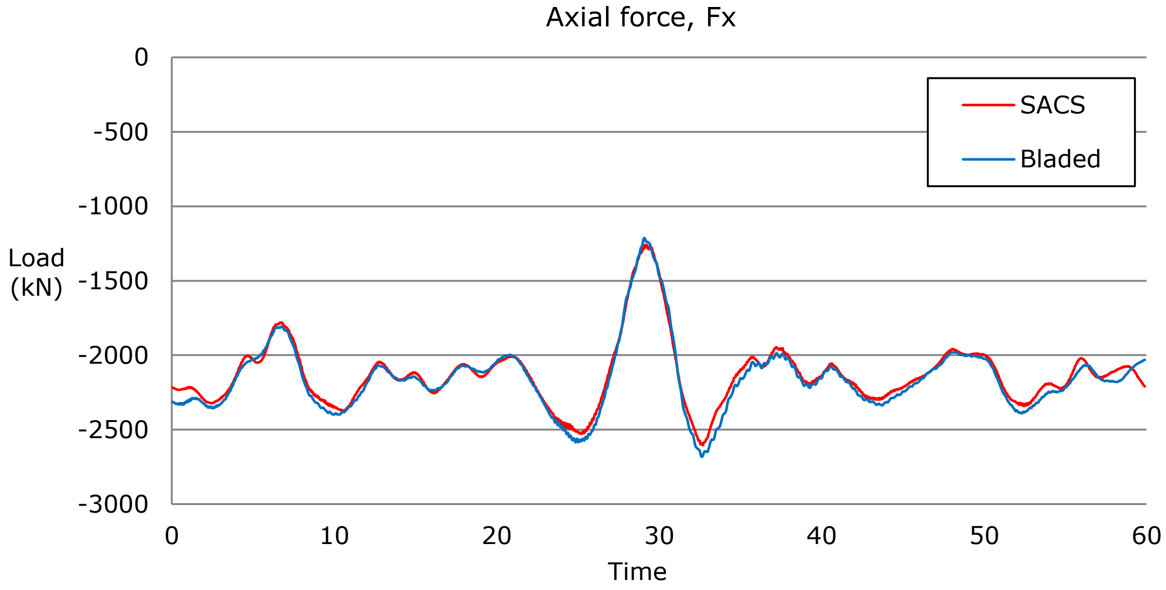

Figure 4-7: Extreme sea state, axial force in Member 133

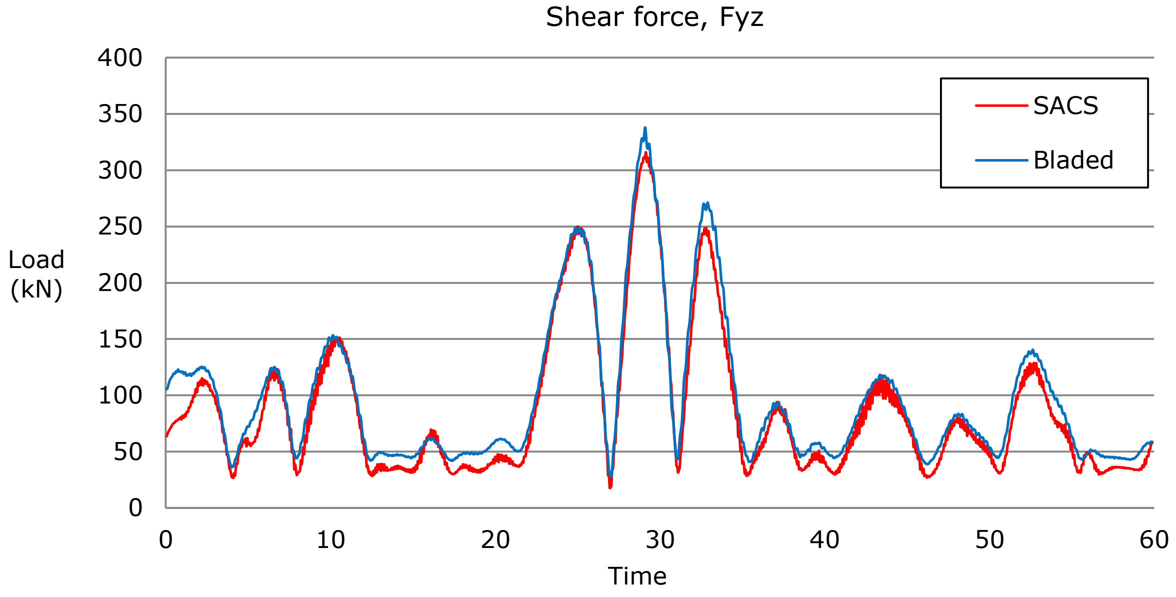

Figure 4-8: Extreme sea state, shear force in Member 133

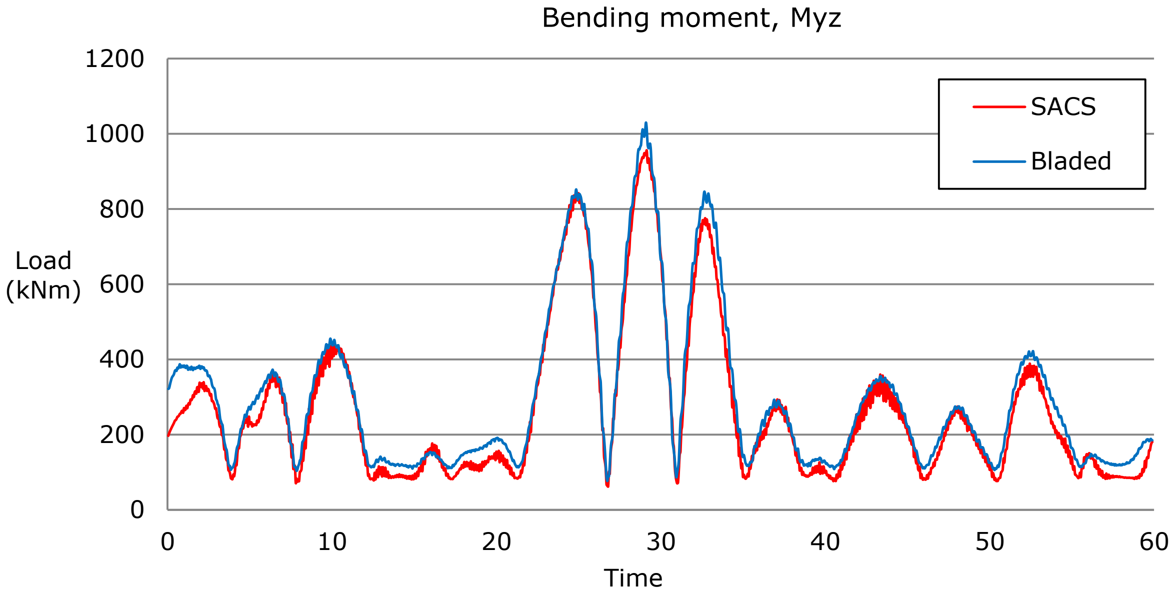

Figure 4-9: Extreme sea state, bending moment in Member 133

4.1.4 Extreme loading comparison summary

The extreme loads calculated from the SACS and Bladed time histories and the percentage difference between them are presented in Table 4-1. There is a good agreement in extreme load predictions, with differences between 0.8 and 7.8%.

		SACS	Bladed	% difference
Member 67	Axial force, Fx (kN)	2507	2488	0.8
	Shear force, Fyz (kN)	58	57	2.8
	Bending moment, Myz (kNm)	103	95	7.4
Member 81	Axial force, Fx (kN)	1939	1912	1.4
	Shear force, Fyz (kN)	129	133	-3.6
	Bending moment, Myz (kNm)	476	485	-2.1
Member 133	Axial force, Fx (kN)	-1260	-1213	3.7
	Shear force, Fyz (kN)	316	338	-7.0
	Bending moment, Myz (kNm)	955	1030	-7.8

Table 4-1: Extreme load results comparison

4.2 Fatigue Loading

Fatigue loading time history comparisons are presented in this section. The simulation was 600 seconds long, but a 100 second sample is presented for visual comparison. For brevity, only the time histories from Member 133 are presented.

4.2.1 Fatigue loading: Member 133

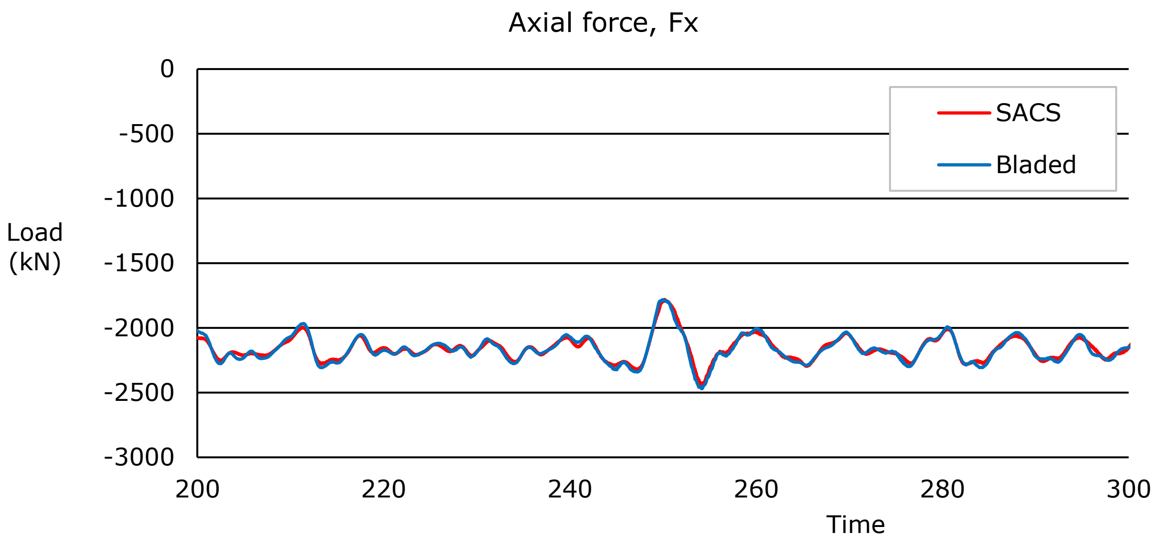

Figure 4-10: Fatigue sea state, axial force in Member 133

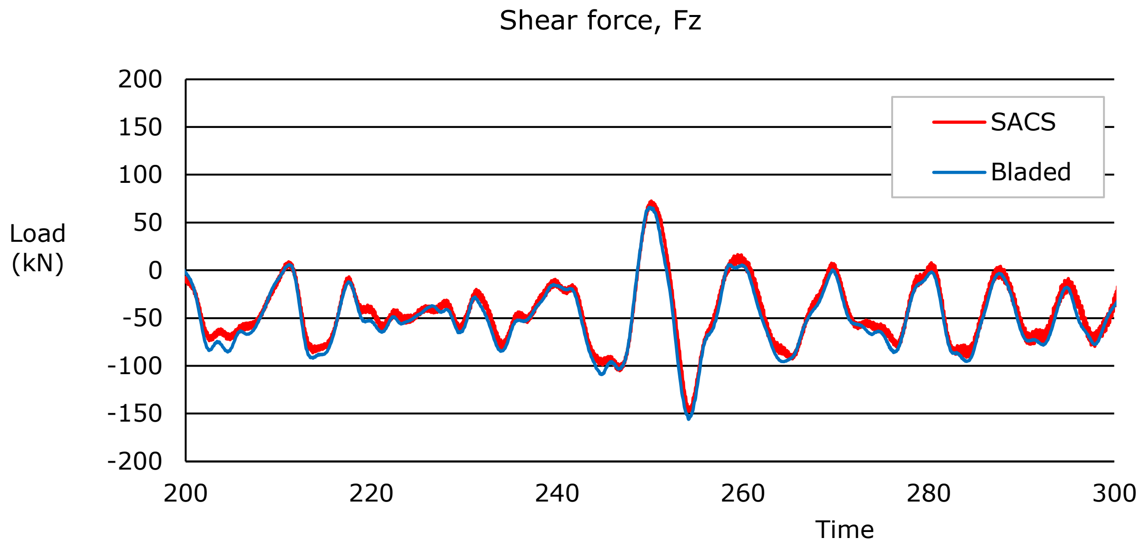

Figure 4-11: Fatigue sea state, shear force in Member 133

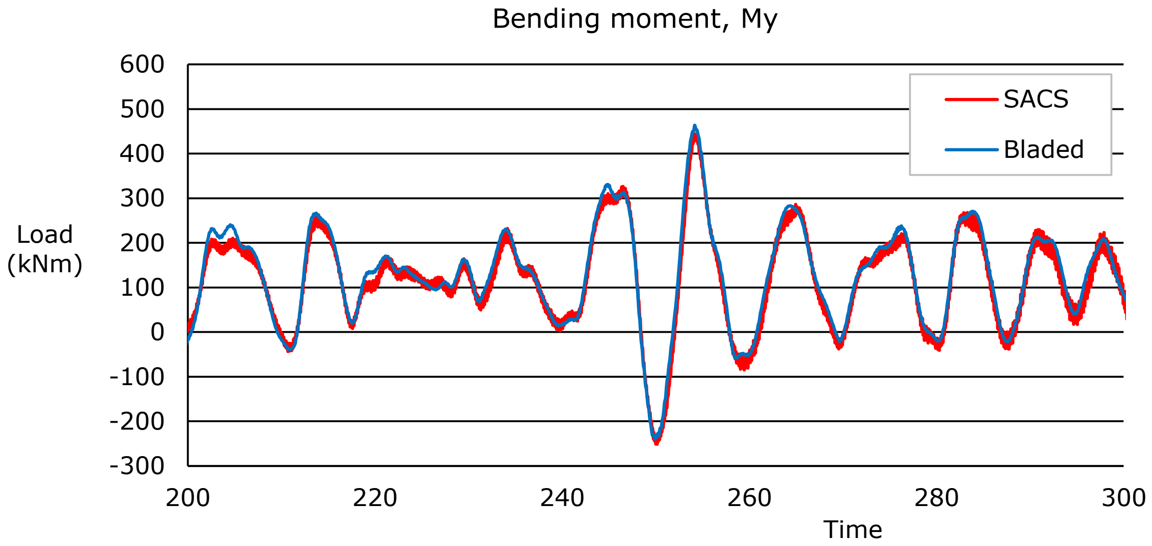

Figure 4-12: Fatigue sea state, bending moment in Member 133

4.2.2 Fatigue loading comparison summary

The fatigue time histories from Bladed and SACS were used to calculate damage equivalent loads, assuming a 20 year turbine lifetime with 10^7 cycles and an inverse SN slope value of 4. The calculation of damage equivalent loads is described in [2]. The results are shown in Table 4-2. There is a good agreement in fatigue load predictions, with differences from 0.9 to 8.0 percent.

		Bladed	SACS	% difference
Member 67	Axial Force (kN)	311	302	2.9
	Shear Force (kN)	21	23	-7.8
	Bending Moment (kNm)	45	45	-1.0
Member 81	Axial Force (kN)	87	91	-4.4
	Shear Force (kN)	72	74	-1.8
	Bending Moment (kNm)	225	222	0.9
Member 133	Axial Force (kN)	634	587	8.0
	Shear Force (kN)	199	202	-1.4
	Bending Moment (kNm)	628	639	-1.8

Table 4-2: Fatigue Damage Equivalent Load results comparison

5 CONCLUSIONS

Bladed verified against SACS

Dynamic analyses of an offshore wind turbine support structure subject to wave loading have been carried out in Bladed and SACS. The member loading was compared at three locations in the jacket structure. The difference in extreme loading ranged from 0.8 to 7.8 percent. The difference in fatigue damaged equivalent load ranged from 0.9 to 8.0 percent.

Cost reduction benefit of integrated design

Integrated analysis tools such as Bladed can be used to carry out integrated design of offshore wind turbine support structures. As Bladed and SACS have been shown to give similar wave loading predictions, support structure designers can be confident to move to an integrated design process rather than a sequential design process. The key advantage of integrated design is a fully coupled loads analysis, leading to a lower cost of energy by achieving more structurally efficient designs with fewer design iterations.

REFERENCES

1. Fully Integrated Design: Lifetime Cost of Energy Reduction for Offshore Wind**,** *Dobbin et al*

2. Bladed Theory Manual