Appendix to report:

SBJ-33-C5-OON-22-RE-015-B

K12 - SHIP IMPACT, BRIDGE GIRDER

Appendix title:

APPENDIX C – SENSITIVITY OF SHIP IMPACT RESPONSE

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CONCEPT DEVELOPMENT FLOATING BRIDGE E39 BJØRNAFJORDEN

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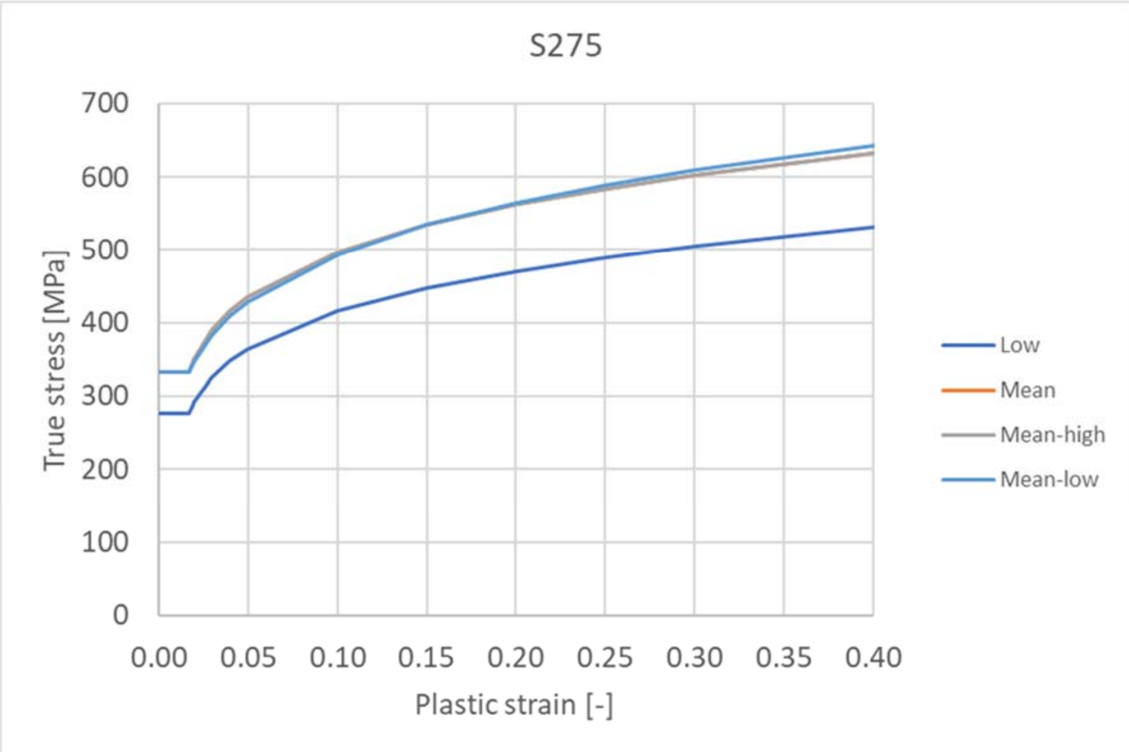
1 SENSITIVITY OF MATERIAL PARAMETERS

This section investigates the sensitivity of material parameters. The material damage model used is the BWH model with mesh scaling. The different material parameters chosen are shown in Table 1-1. The resulting material curves are shown in Figure 1-1 and Figure 1-2. S275 is utilized for the deckhouse ship and S420 for the bridge girder.

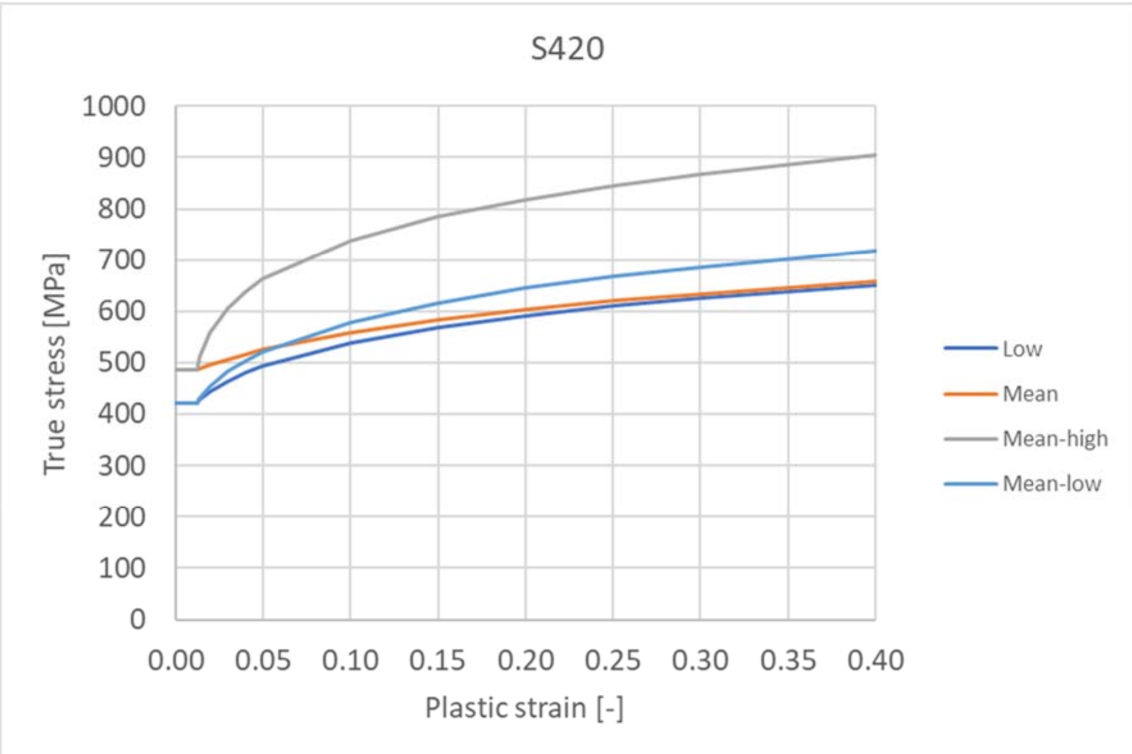
> *Table 1-1 Material parameters for sensitivity analyses*

Name	Steel quality	Yield stress[1]	$\varepsilon_{plateau}$	K	n
Low[2]	S275	276.5 MPa	0.017	620 MPa	0.166
	S420	422.5 MPa	0.012	738 MPa	0.140
Mean[3]	S275	331.8 MPa	0.017	740 MPa	0.166
	S420	485.9 MPa	0.011928571	738 MPa	0.140
Mean-high[4]	S275	331.8 MPa	0.017	740 MPa	0.166
	S420	485.9 MPa	0.011928571	1030 MPa	0.140
Mean-low[5]	S275	331.8 MPa	0.017	764 MPa	0.185
	S420	422.5 MPa	0.012	827 MPa	0.155

[1] For thicknesses 16 mm and below
[2] Equal to material in section 4.2 [4], bullet 1
[3] Parameters according to DNVGL-RP-C208 [7] section 7.8
[4] Yield stress, $\varepsilon_{plateau}$ and n according to DNVGL-RP-C208 [7] section 7.8, K according to section 4.2 [4], bullet 2.c and 2.d
[5] Equal to material in section 4.2 [4], bullet 2



> *Figure 1-1 True stress-strain curves of the S275 steel materials for sensitivity analyses ("mean" and "mean-high" are equal)*

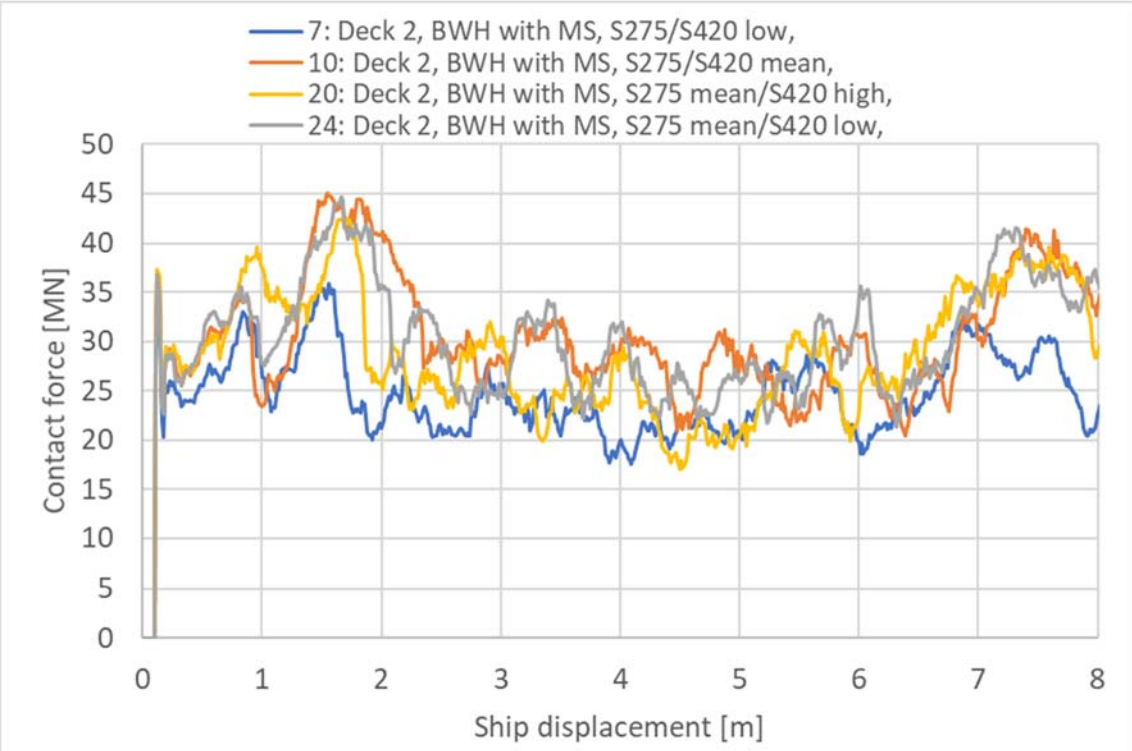


> *Figure 1-2 True stress-strain curves of the S420 steel materials for sensitivity analyses*

Figure 1-3, Figure 1-4 and Figure 1-5 show the force-displacement curves for the sensitivity check of material parameters for impact at deck 2, inclined at deck 4 and between deck 2 and 3, respectively. The choice of material parameters affects the collision response. The initial impact is almost identical with "mean", "mean-low" and "mean-high" material, while the "low" material results in lower impact force. The reason is because the simulation is more sensitive to a change in material parameters of the deckhouse (S275, see Figure 1-1) than the bridge girder (S420, see Figure 1-2) since the deckhouse is more damaged in collision with the bridge girder.

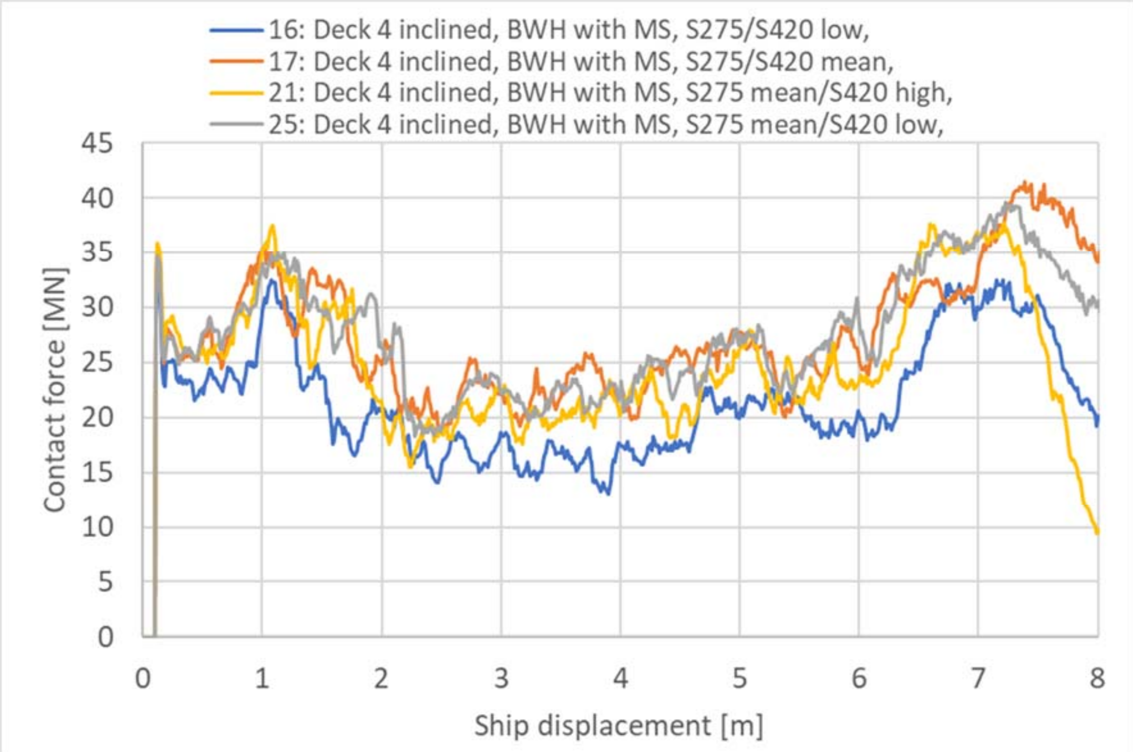
The "low" material is a set of parameters intended for design calculations. The design parameters may result in too low capacity for structures when the goal is to evaluate the impact forces. On the other hand, the "mean-high" material is considered too conservative. Since the bridge is designed utilizing low material properties, the "mean-low" material seems more holistic to utilize for the bridge girder when evaluating the ship impact response. The "mean-low" material parameters are also close to the material parameters chosen for the work performed at NTNU [1] and by the suspension bridge group [2] in the previous phases of the Bjørnafjorden project.

ID-no.	Max. contact force [MN] 0-8 m	Mean contact force [MN] 0-8 m
7	36	25
10	45	31
20	43	29
24	45	31



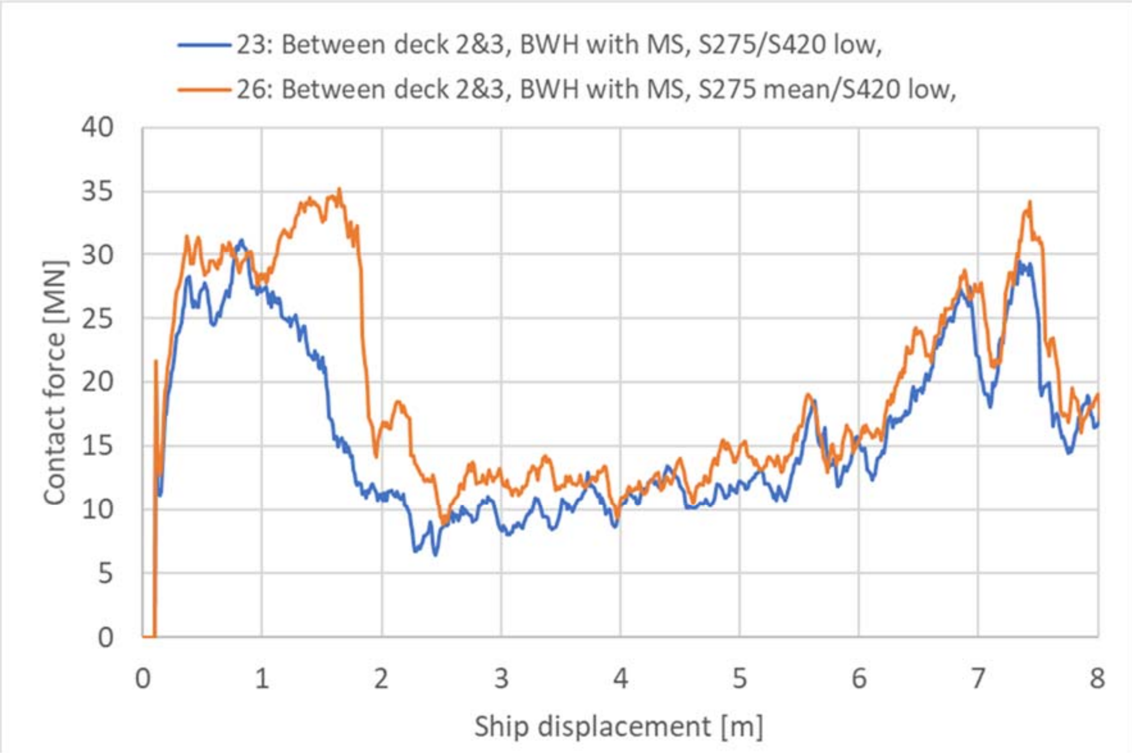
> *Figure 1-3 Contact force [MN] impact deckhouse-girder at deck 2, sensitivity of material parameters*

ID-no.	Max. contact force [MN] 0-8 m	Mean contact force [MN] 0-8 m
16	33	21
17	41	28
21	38	25
25	40	28



> *Figure 1-4 Contact force [MN] impact deckhouse-girder inclined at deck 4, sensitivity of material parameters*

ID-no.	Max. contact force [MN] 0-8 m	Mean contact force [MN] 0-8 m
23	31	16
26	35	19

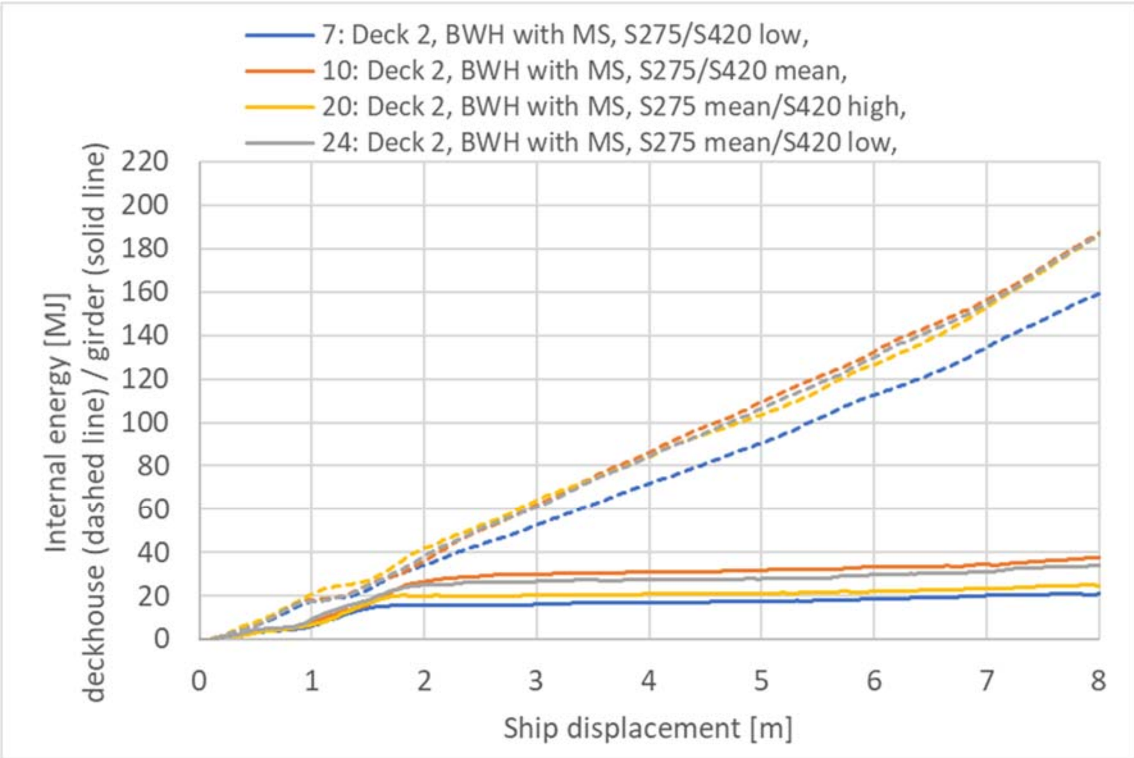


> *Figure 1-5 Contact force [MN] impact deckhouse-girder between deck 2 and 3, sensitivity of material parameters*

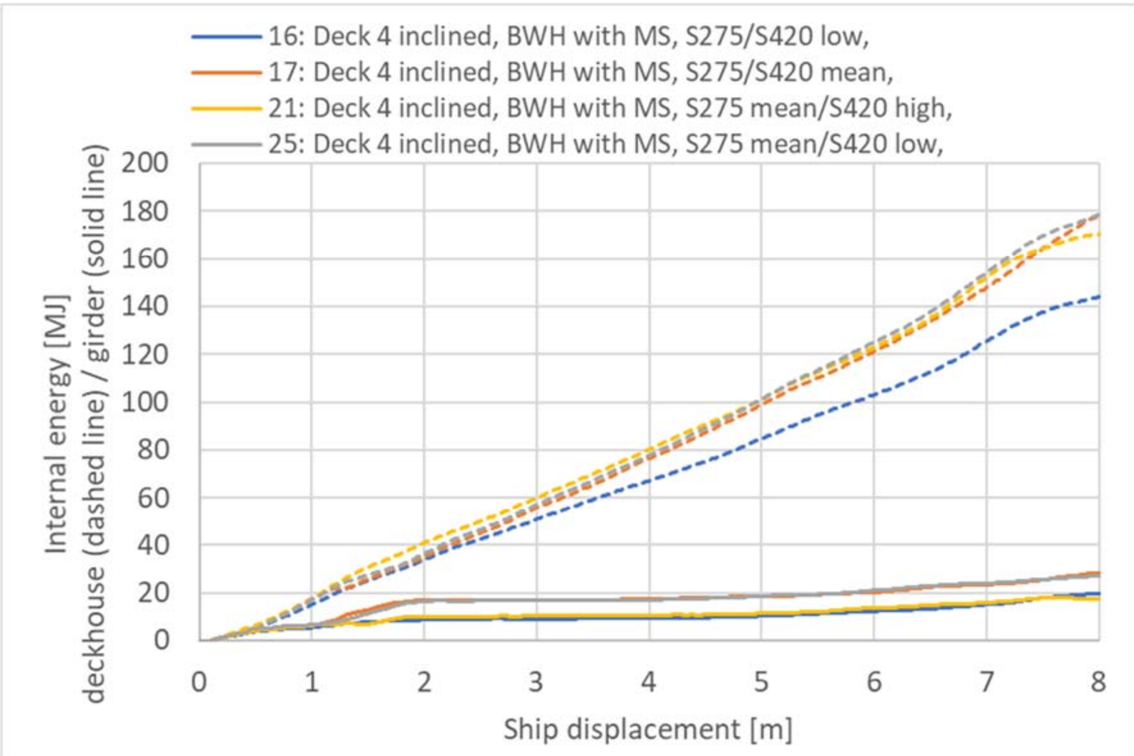
Figure 1-6, Figure 1-7 and Figure 1-8 show the internal energy dissipated in the deckhouse with dashed line and the bridge girder with solid line. The internal energy is similar for all materials, except for the models with "low" material which have lower internal energy in especially the deckhouse. The bridge girder is less sensitive for the choice of material parameters than the deckhouse because the bridge girder is less damaged.

Figure 1-9, Figure 1-10 and Figure 1-11 show the frictional dissipation and artificial energy in the models. The proportion of artificial to internal energy is 8-11 % for the displayed models.

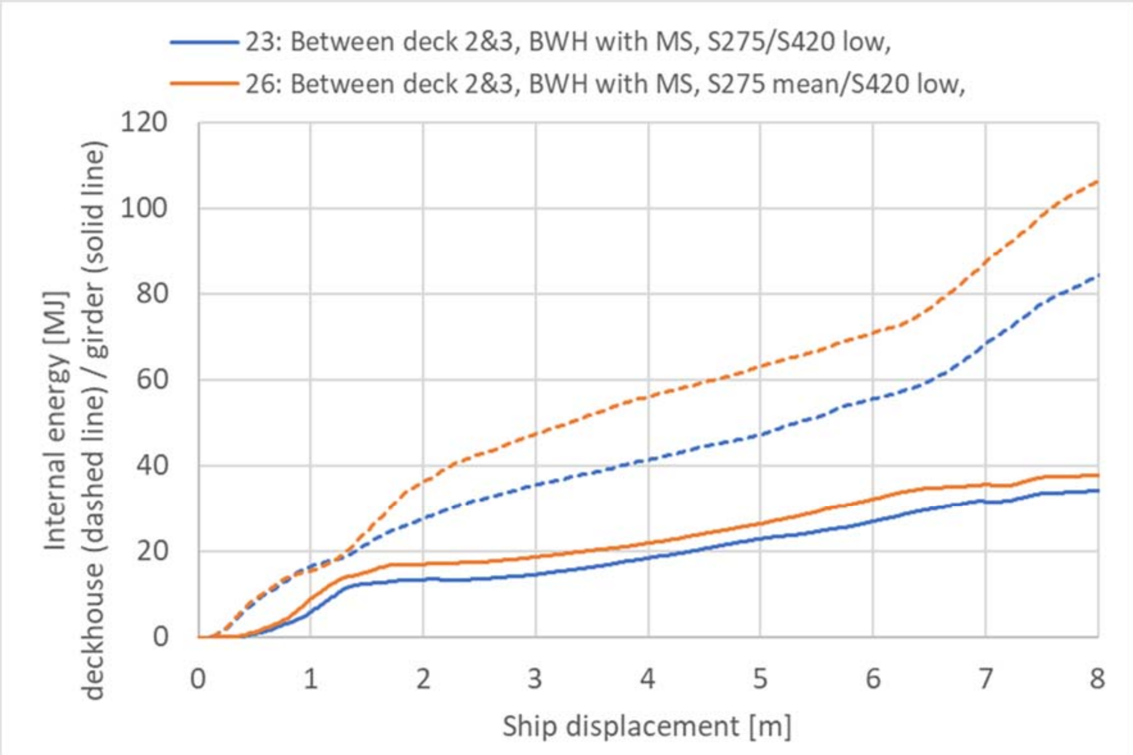
Figure 1-12, Figure 1-13 and Figure 1-14 show the proportion of internal energy dissipated in the bridge girder. The dissipated energy is low for impact at deck 2 and inclined at deck 4, and higher between deck 2 and 3. The "mean" and "mean-low" material gives a bit higher energy dissipation in the bridge girder for impact at deck 2 and inclined at deck 4. Impact between deck 2 and 3 does now show this. It is difficult to draw any conclusions to how the material curve affects the proportion of energy dissipated in the girder.



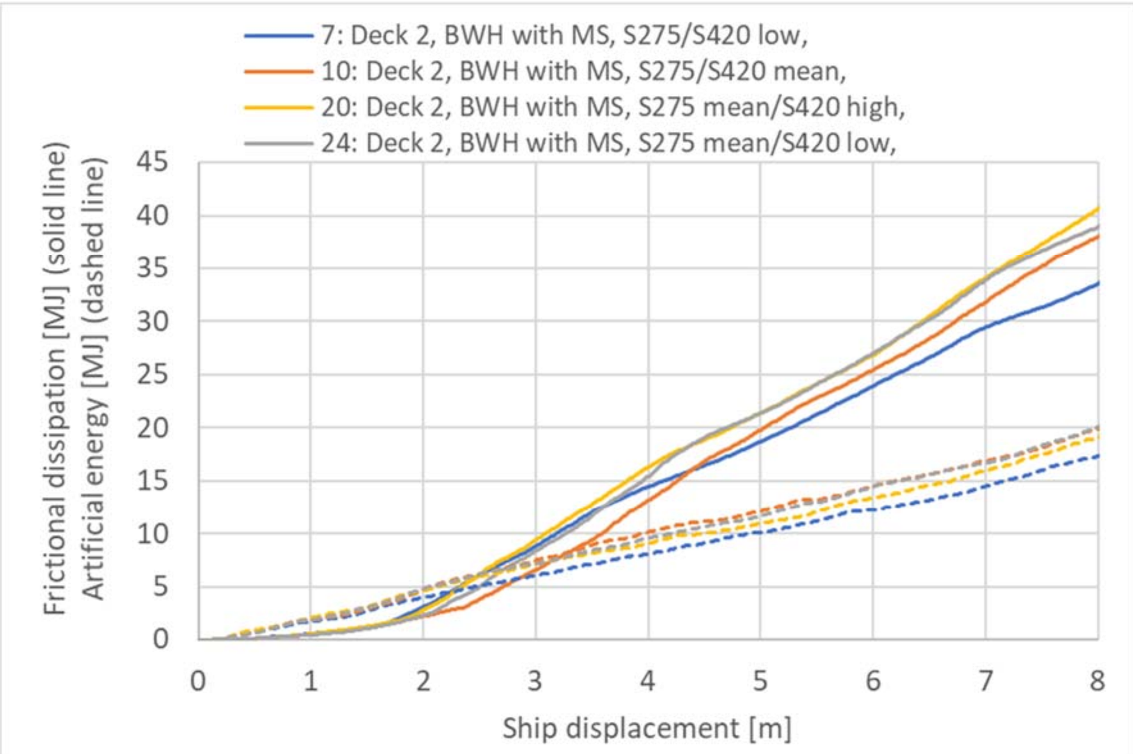
> *Figure 1-6 Internal energy [MJ] impact deckhouse-girder at deck 2, sensitivity of material parameters*



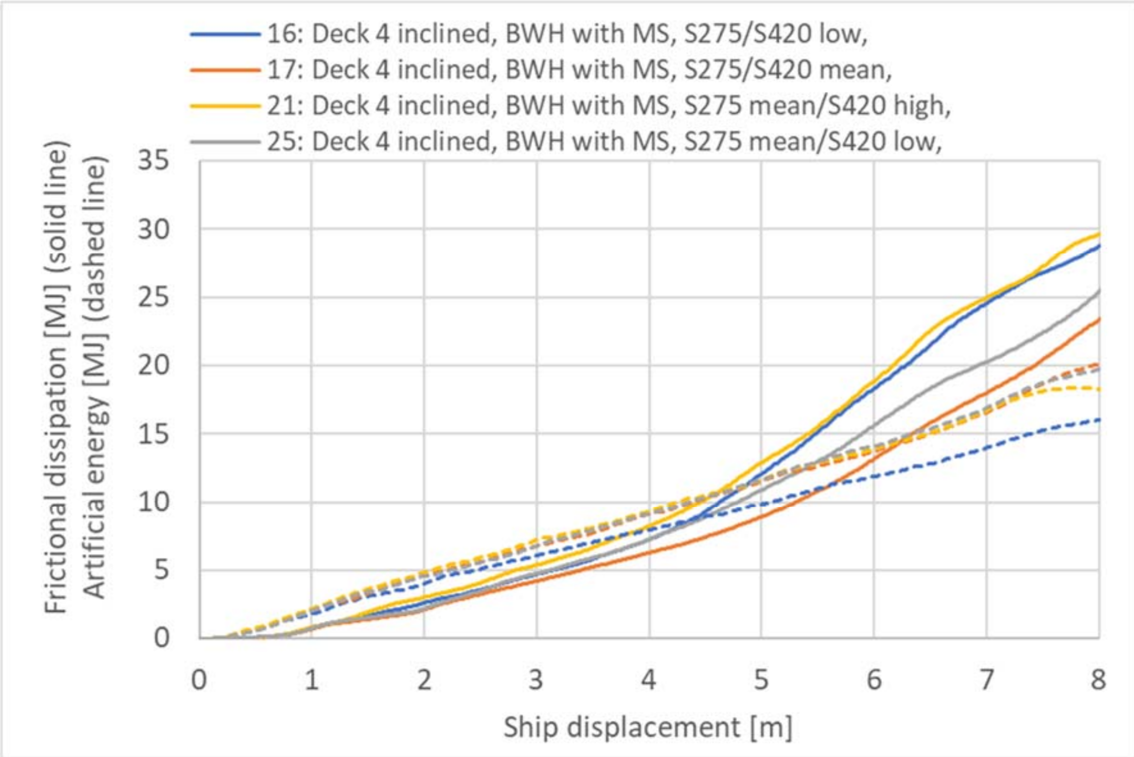
> *Figure 1-7 Internal energy [MJ] impact deckhouse-girder inclined at deck 4, sensitivity of material parameters*



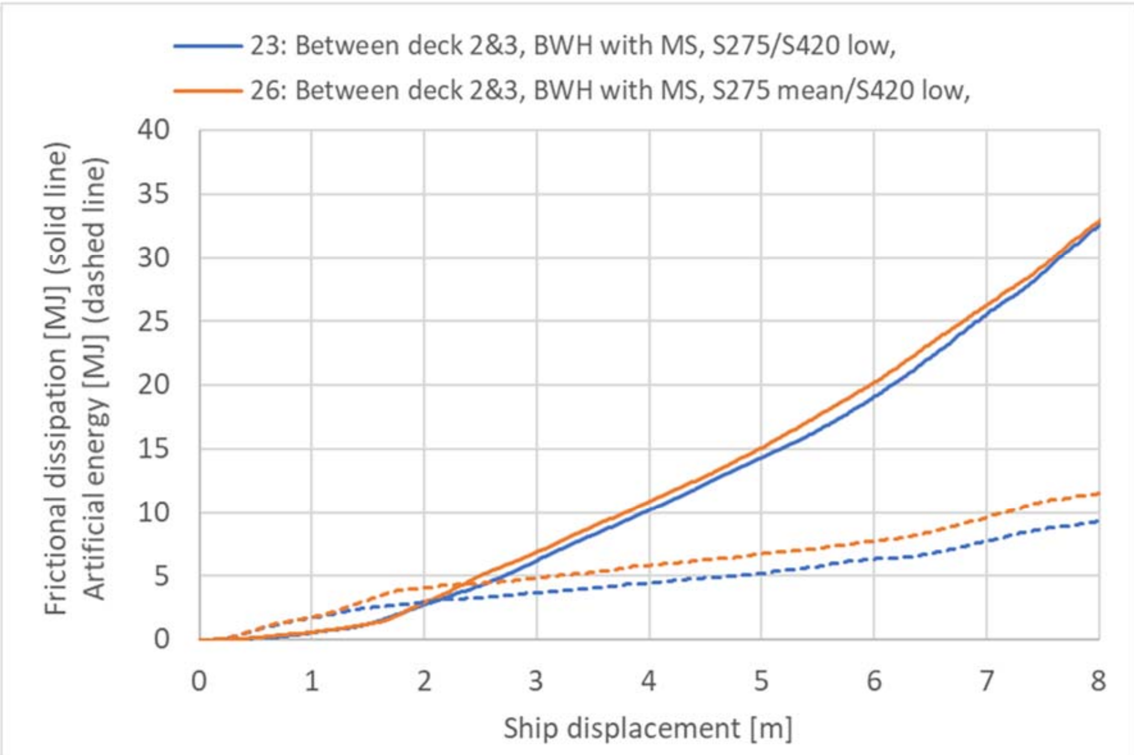
> *Figure 1-8 Internal energy [MJ] impact deckhouse-girder between deck 2 and 3, sensitivity of material parameters*



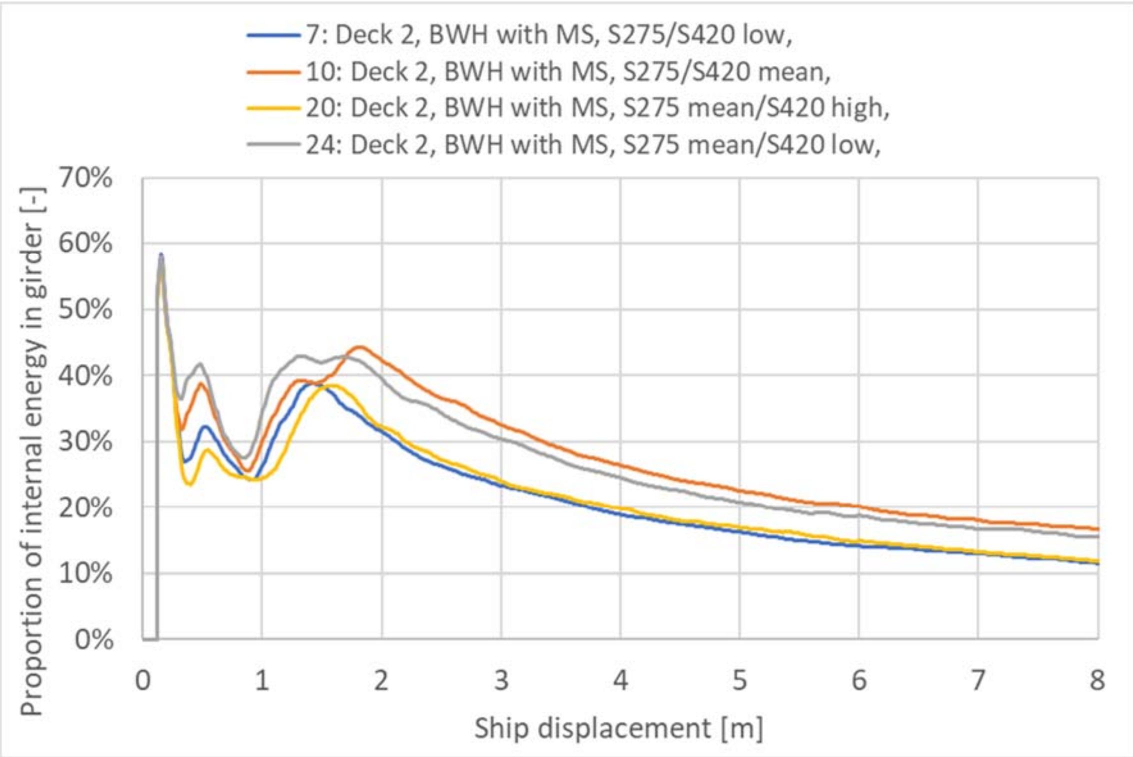
> *Figure 1-9 Frictional dissipation and artificial energy [MJ] impact deckhouse-girder at deck 2, sensitivity of material parameters*



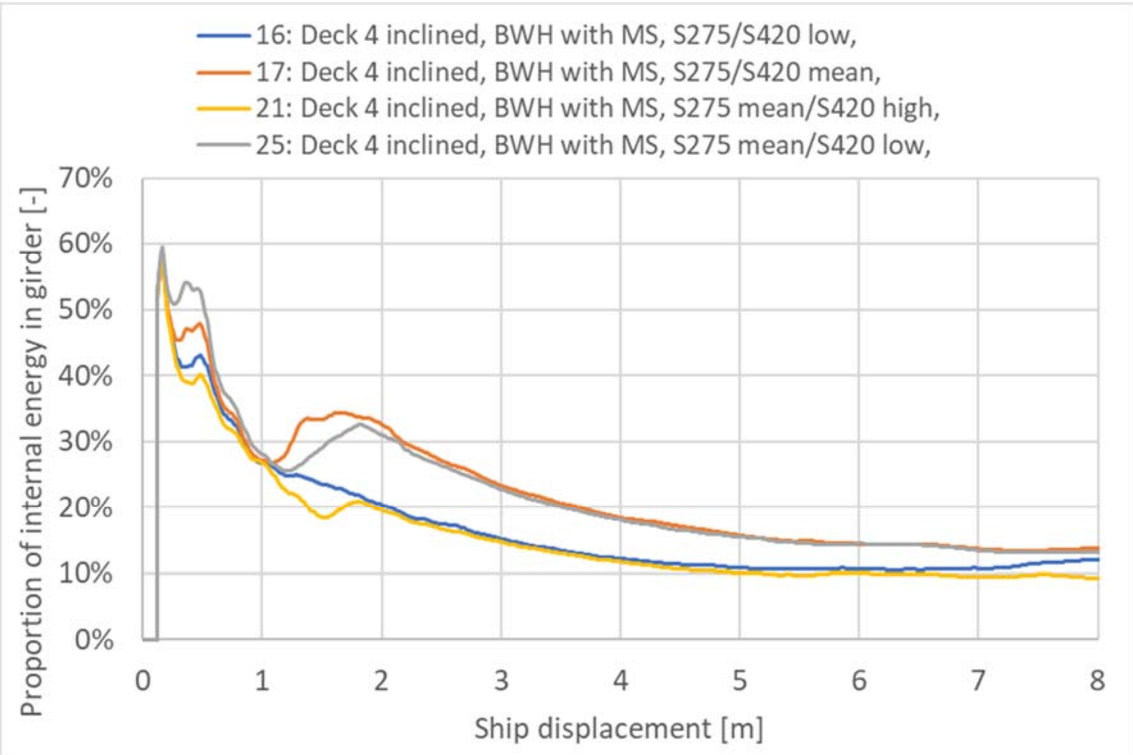
> *Figure 1-10 Frictional dissipation and artificial energy [MJ] impact deckhouse-girder inclined at deck 4, sensitivity of material parameters*



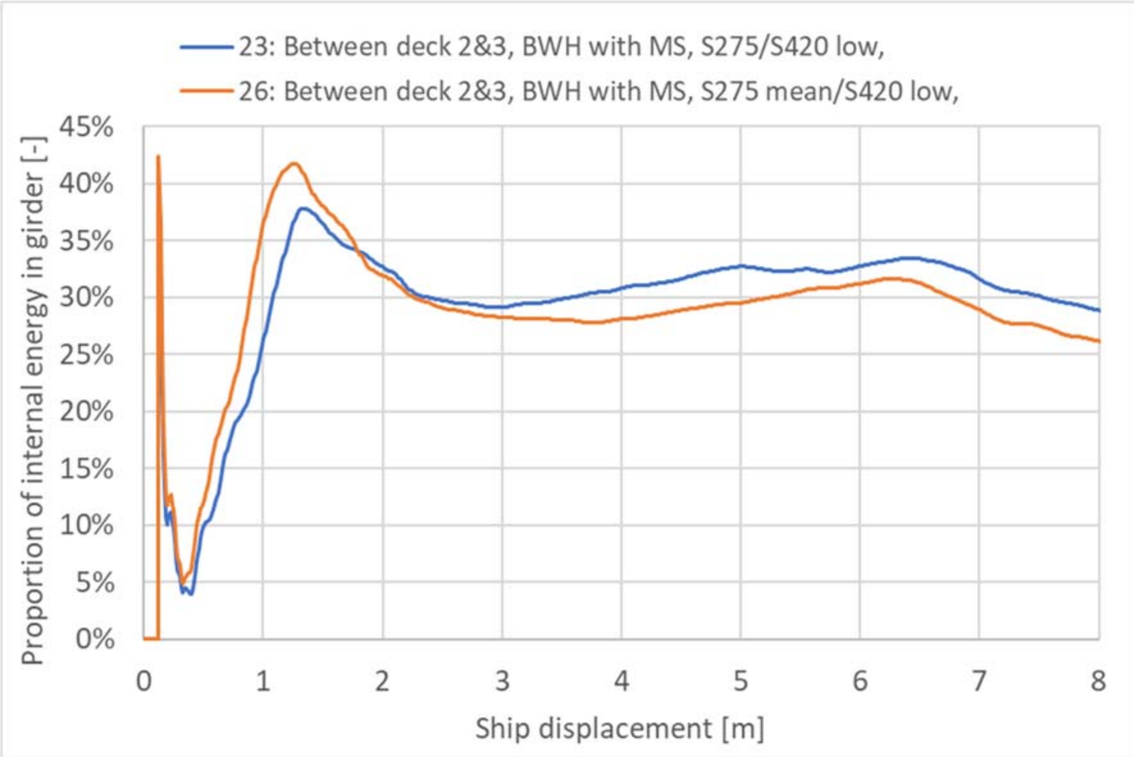
> *Figure 1-11 Frictional dissipation and artificial energy [MJ] impact deckhouse-girder between deck 2 and 3, sensitivity of material parameters*



> *Figure 1-12 Proportion of internal energy in girder [-] impact deckhouse-girder at deck 2, sensitivity of material parameters*



> *Figure 1-13 Proportion of internal energy in girder [-] impact deckhouse-girder inclined at deck 4, sensitivity of material parameters*

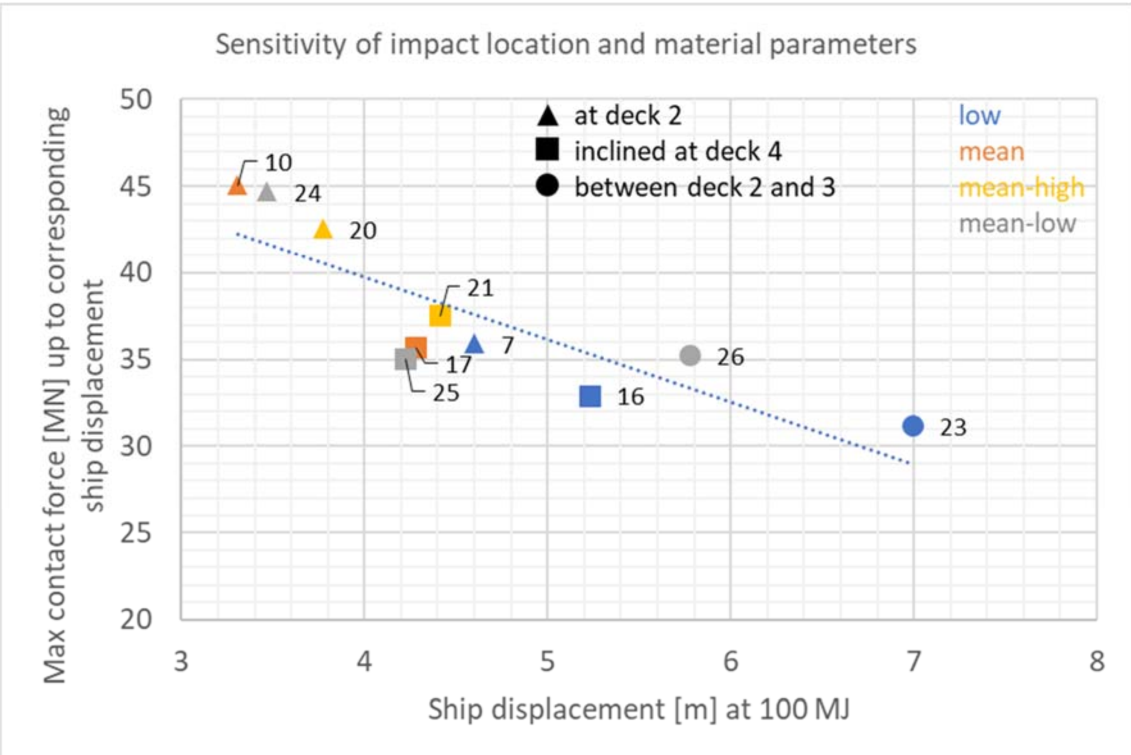


> *Figure 1-14 Proportion of internal energy in girder [-] impact deckhouse-girder between deck 2 and 3, sensitivity of material parameters*

Figure 1-15 shows a graphical presentation of the sensitivity of the material parameters investigated for impact with the deckhouse. An equal value of the dissipated internal energy in the local simulations is chosen, 100 MJ. This is about 25 % of the energy to be dissipated for impact at the bridge girder (385 MJ). Then, the maximum contact force occurred from 0 m ship displacement to ship displacement corresponding 100 MJ for the respective simulation is evaluated. I.e. the maximum force from Figure 1-3 to Figure 1-5, defined by a cut-off at 100 MJ for the respective simulation.

Again, it is seen that the "mean-high", "mean-low" and "mean" sets of material parameters give similar results of ship displacement at 100 MJ and maximum contact force up to this displacement. The low fractile set of material parameters gives lower maximum contact force and higher ship displacement. The simulation is more sensitive to a change in material parameters of the deckhouse than the bridge girder since the deckhouse is more damaged in collision with the bridge girder.

The simulation is also sensitive to impact location; the lower the higher force and energy level and at a deck results in higher force and energy level than between decks.



> *Figure 1-15 Sensitivity of impact location and material parameters*

2 SENSITIVITY OF MATERIAL DAMAGE MODELS

This section investigates the sensitivity of material damage models. Three sets of analysis have been conducted, which have also been investigated in Appendix B [3]:

- BWH model without mesh scaling
- BWH model with mesh scaling
- FLD material model with Swift instability

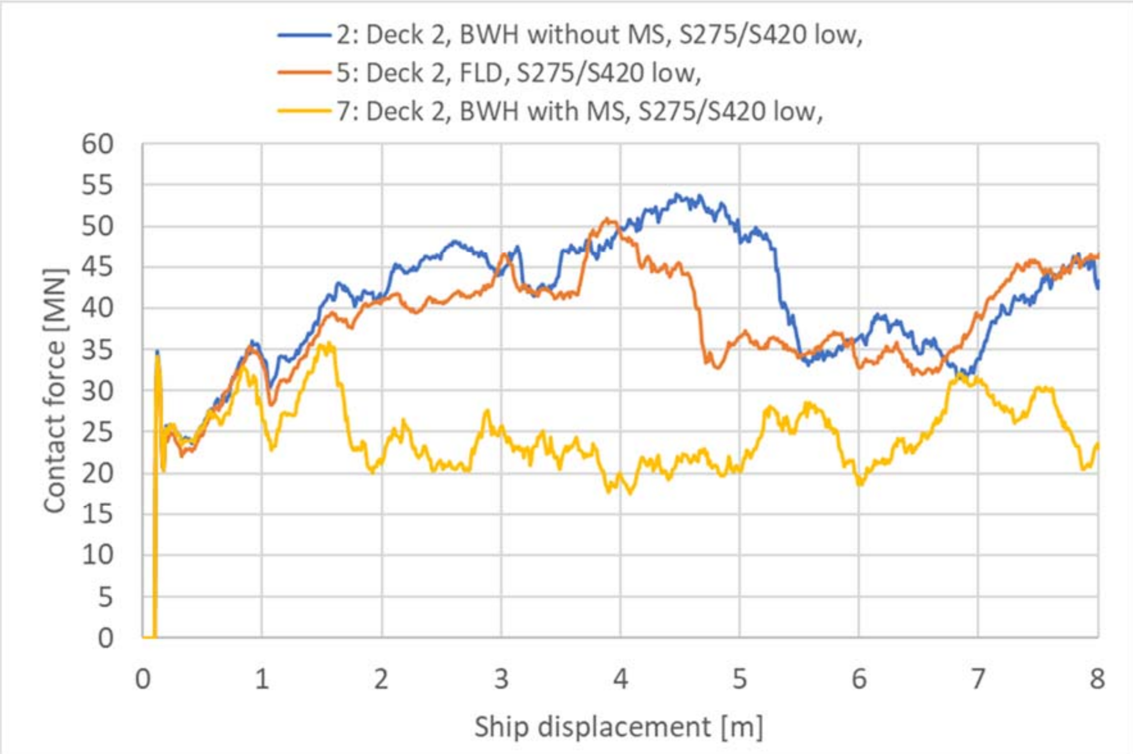
For discussion about the different material damage models, see chapter 3 [4] and Appendix B [3].

Figure 2-1 and Figure 2-2 show the resulting force-displacement curves. The FLD material display similar results as the BWH model without mesh scaling. The BWH model with mesh scaling displays lower force level than the two other models, which is expected.

With reference to the sensitivity model reported in section 3.4.2 [4], the difference in force level is more significant in simulations using the BWH model without mesh scaling than for the simulations where mesh scaling is applied. Since the results for length/thickness (l/t)-ratio=1 without mesh scaling is in the same range as results with mesh scaling and l/t-ratio of 1-25, the full analysis is run utilizing the BWH model with mesh scaling applied to the entire model. The characteristic element length is 100 mm for both the deckhouse and bridge girder, giving l/t-ratio of approximately 5-15.

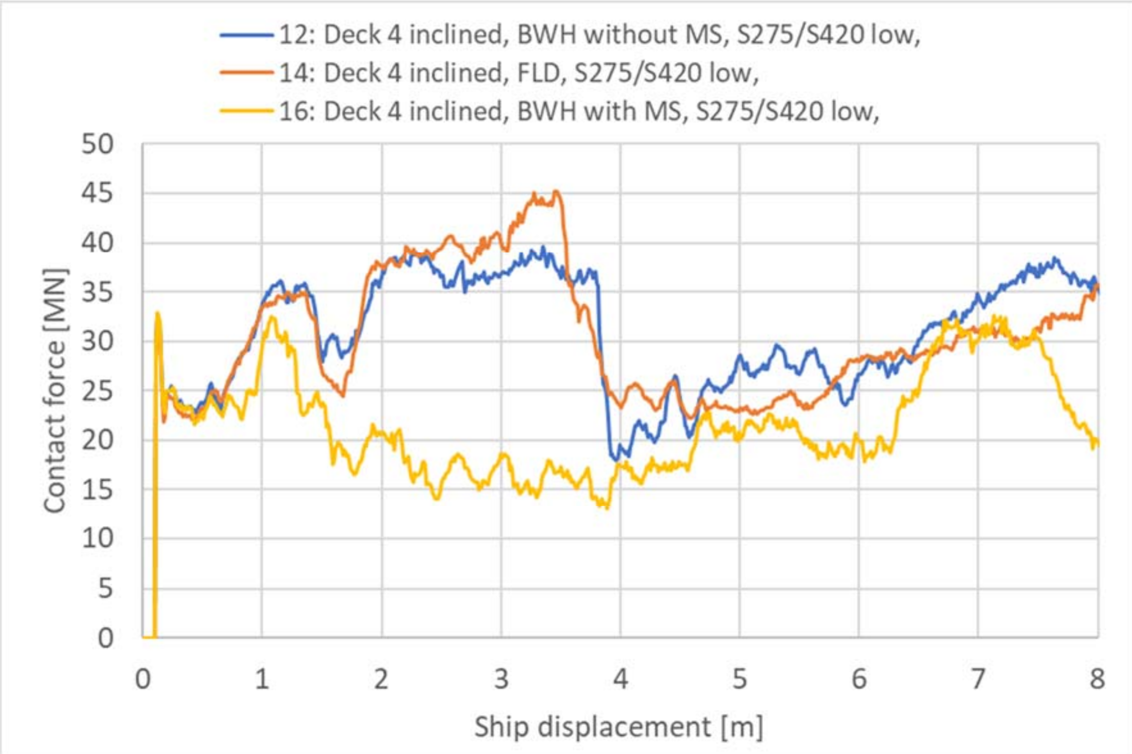
Note that the initial impact is almost identical with the different material damage model, which is also seen for the sensitivity model reported in Appendix B section 2 [3].

ID-no.	Max. contact force [MN] 0-8 m	Mean contact force [MN] 0-8 m
2	54	41
5	51	39
7	36	25



> *Figure 2-1 Contact force [MN] impact deckhouse-girder at deck 2, sensitivity of material damage models*

ID-no.	Max. contact force [MN] 0-8 m	Mean contact force [MN] 0-8 m
12	40	31
14	45	31
16	33	21



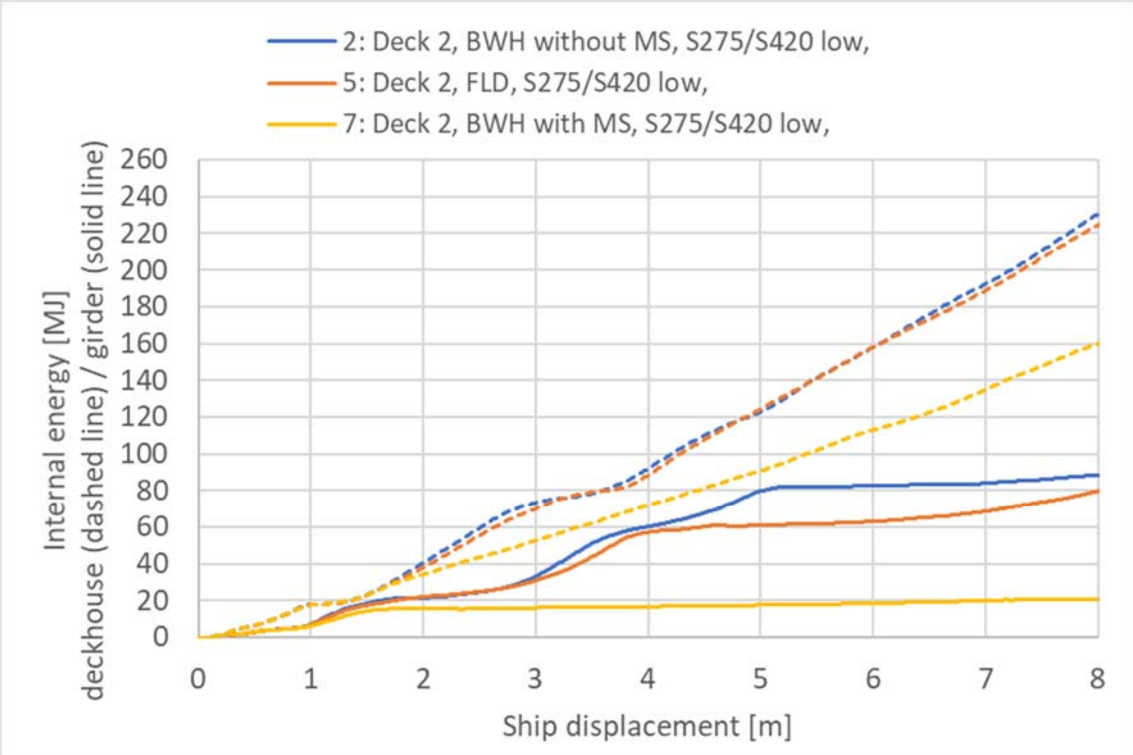
> *Figure 2-2 Contact force [MN] impact deckhouse-girder inclined at deck 4, sensitivity of material damage models*

Figure 2-3 and Figure 2-4 show the internal energy dissipated in the deckhouse with dashed line and the bridge girder with solid line.

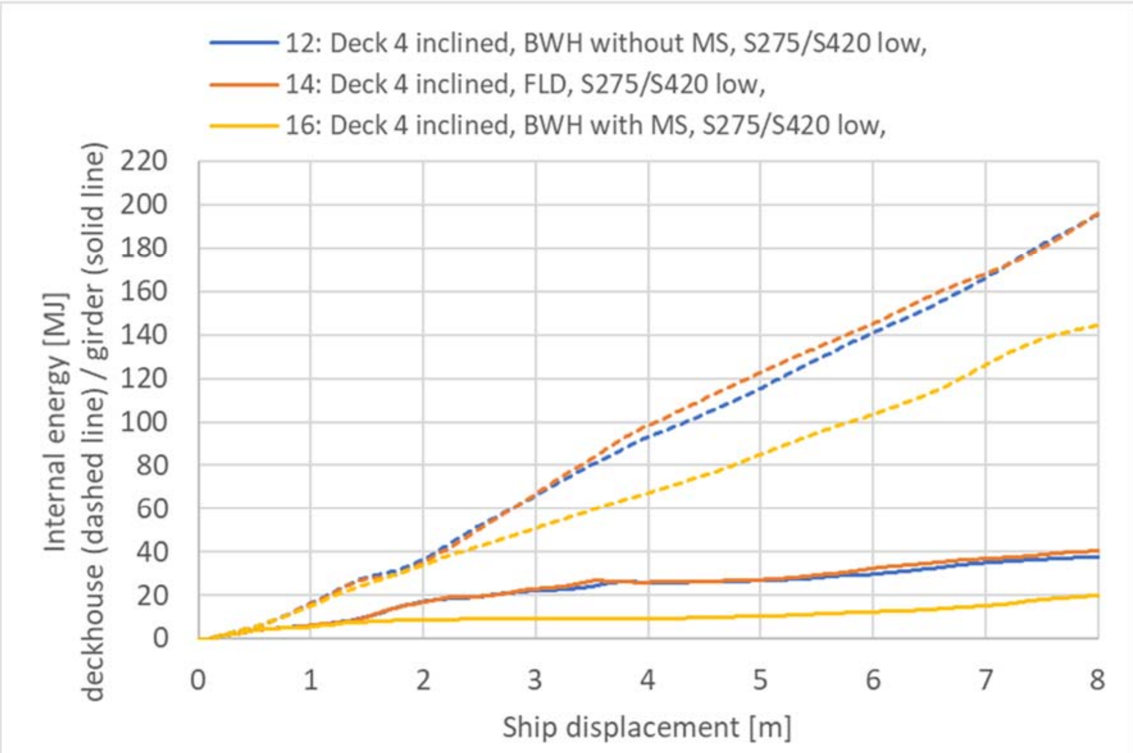
Figure 2-5 and Figure 2-6 show the frictional dissipation and artificial energy in the models. The proportion of artificial to internal energy is 10-12 % for the displayed models.

The simulations with BWH model without mesh scaling and FLD model behave different than the simulations utilizing BWH model with mesh scaling. The internal energy is lower in both deckhouse and bridge girder and the frictional dissipation is higher for the latter. The BWH model without mesh scaling and the FLD model predict fracture at a later state due to coarse mesh, while the BWH model with mesh scaling compensates for this.

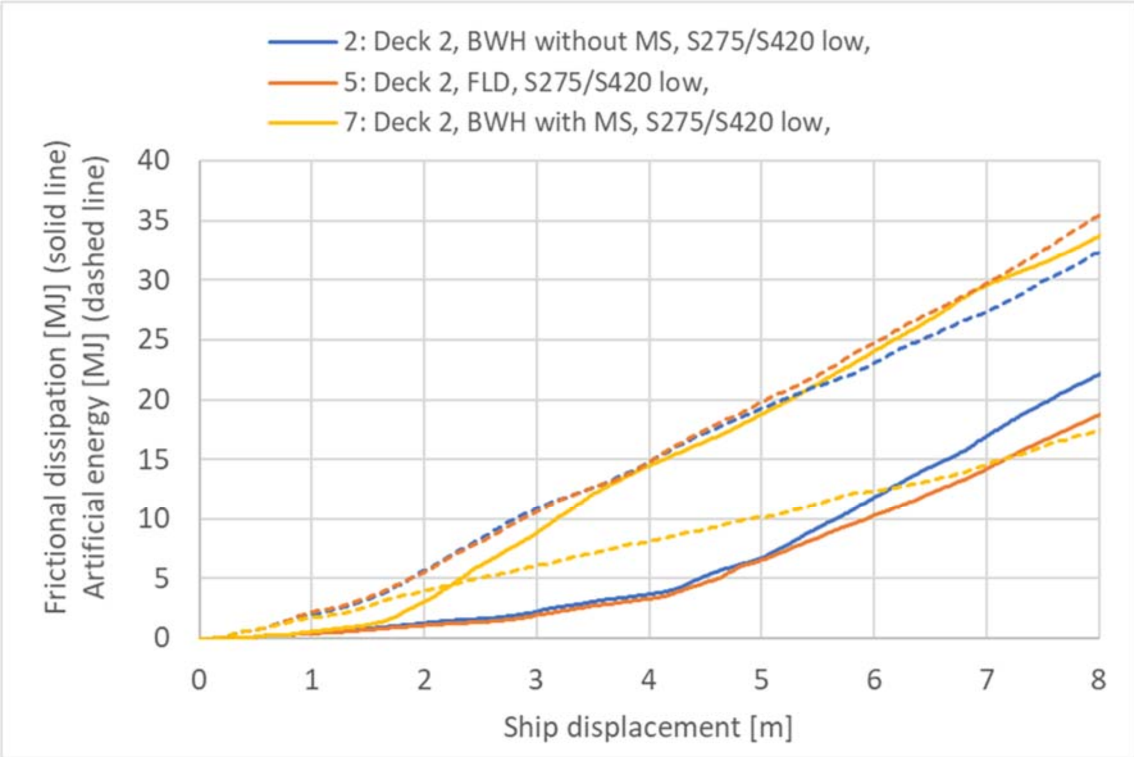
Figure 2-7 and Figure 2-8 show the proportion of internal energy dissipated in the bridge girder. Material damage model BWH with mesh scaling gives a lower energy dissipation in the girder. This is caused by the later fracture prediction of the deckhouse.



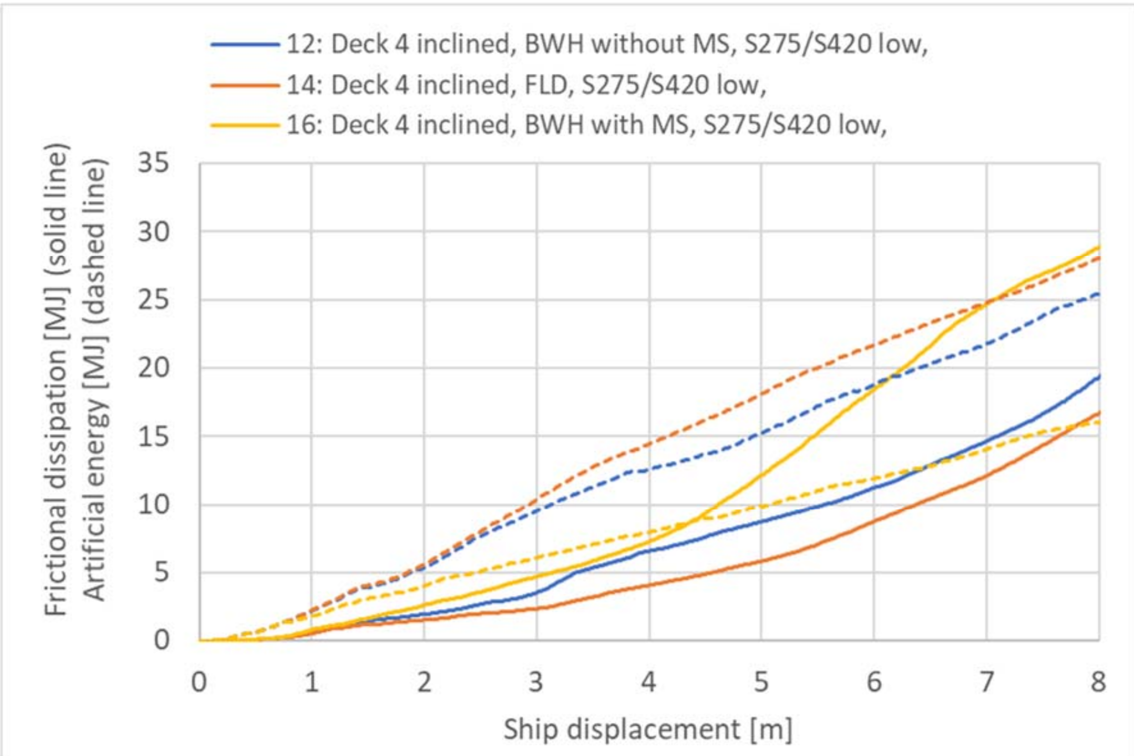
> *Figure 2-3 Internal energy [MJ] impact deckhouse-girder at deck 2, sensitivity of material damage models*



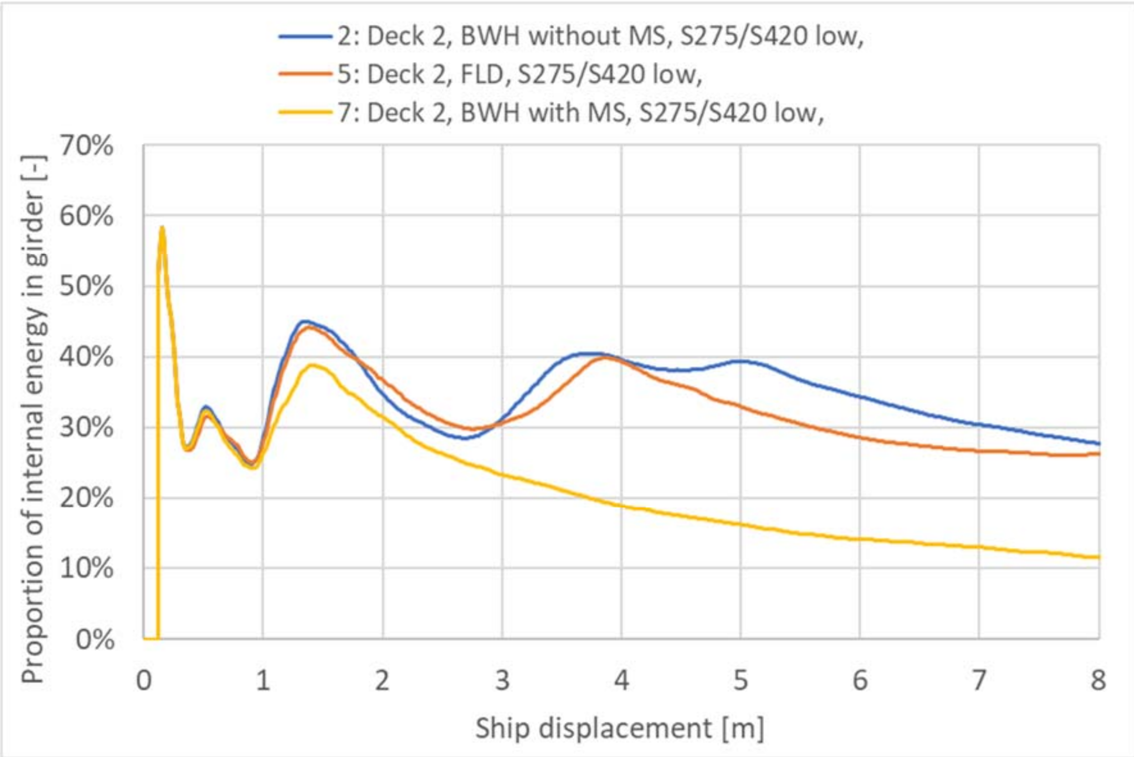
> *Figure 2-4 Internal energy [MJ] impact deckhouse-girder inclined at deck 4, sensitivity of material damage models*



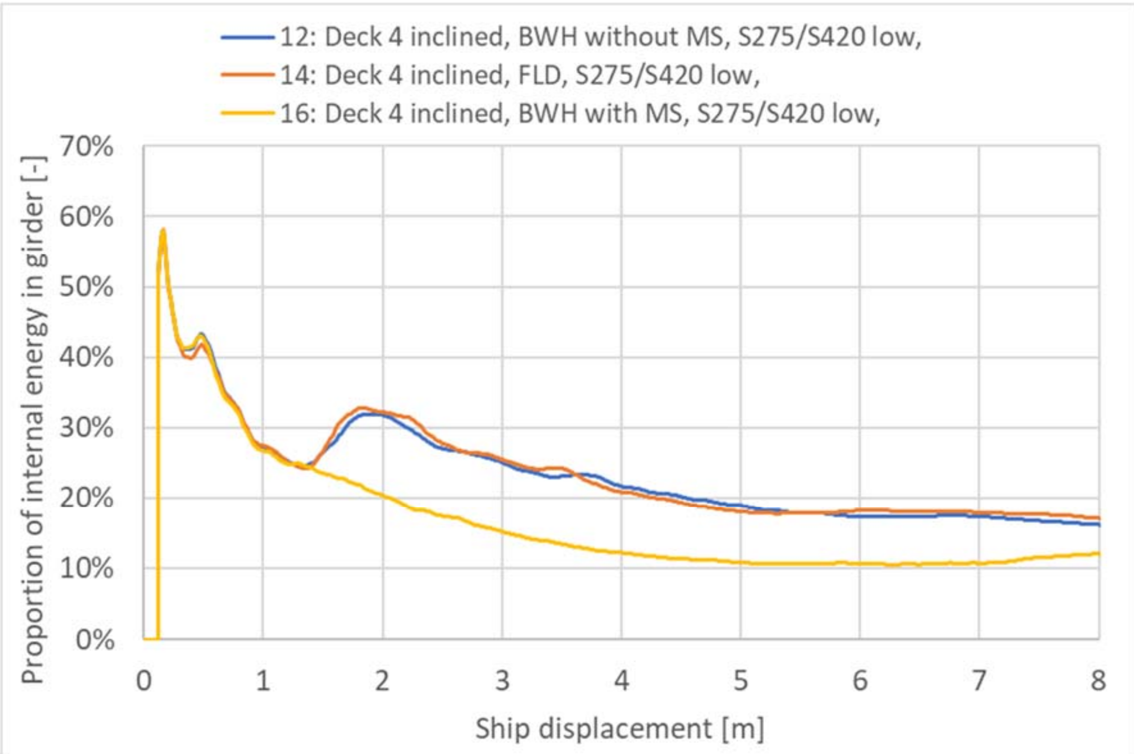
> *Figure 2-5 Frictional dissipation and artificial energy [MJ] impact deckhouse-girder at deck 2, sensitivity of material damage models*



> *Figure 2-6 Frictional dissipation and artificial energy [MJ] impact deckhouse-girder inclined at deck 4, sensitivity of material damage models*



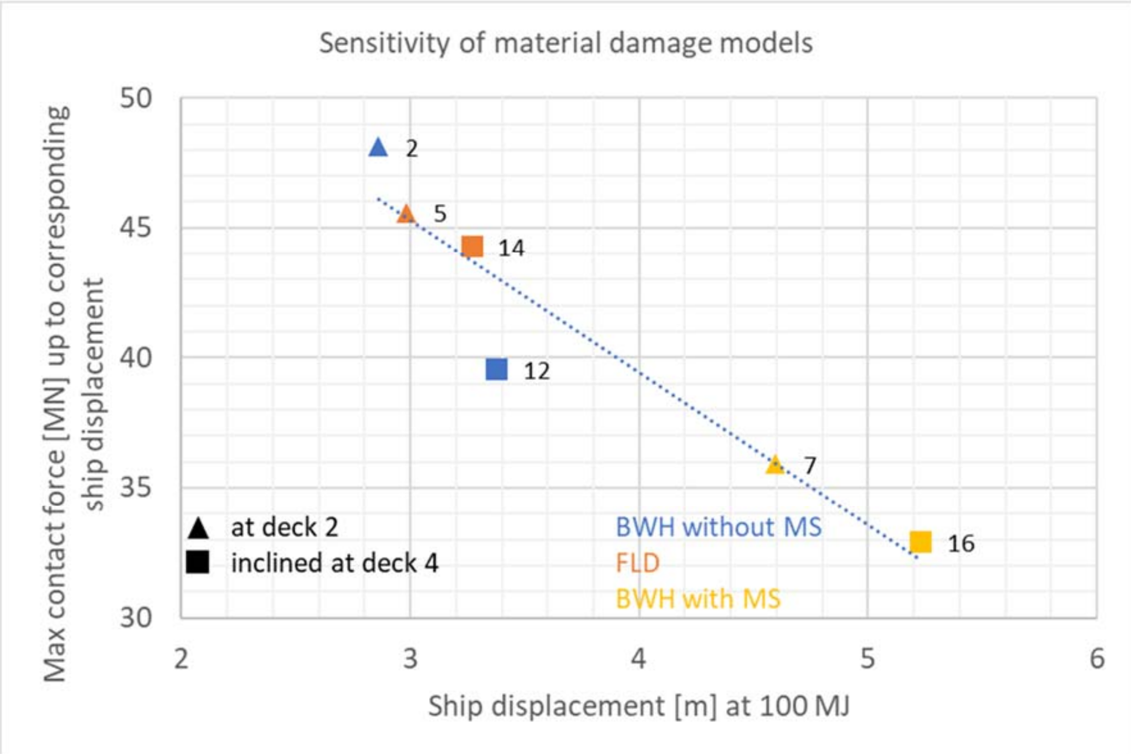
> *Figure 2-7 Proportion of internal energy in girder [-] impact deckhouse-girder at deck 2, sensitivity of material damage models*



> *Figure 2-8 Proportion of internal energy in girder [-] impact deckhouse-girder inclined at deck 4, sensitivity of material damage models*

Figure 2-9 shows a graphical presentation of the sensitivity of the material damage models investigated. The maximum force from Figure 2-1 and Figure 2-2 is plotted, defined by a cut-off at ship displacement corresponding 100 MJ for the respective simulation.

The simulation is sensitive to the material damage model utilized. The FLD material display similar results as the BWH model without mesh scaling. The BWH model with mesh scaling displays lower maximum contact force and higher ship displacement at equal energy dissipation compared to the two other models, which is expected. The material damage model utilized is mainly the BWH model with mesh scaling because the finite element model behaves more independently of the mesh size when mesh scaling is applied.



> *Figure 2-9 Sensitivity of material damage models*

3 SENSITIVITY OF ELEMENT TYPE

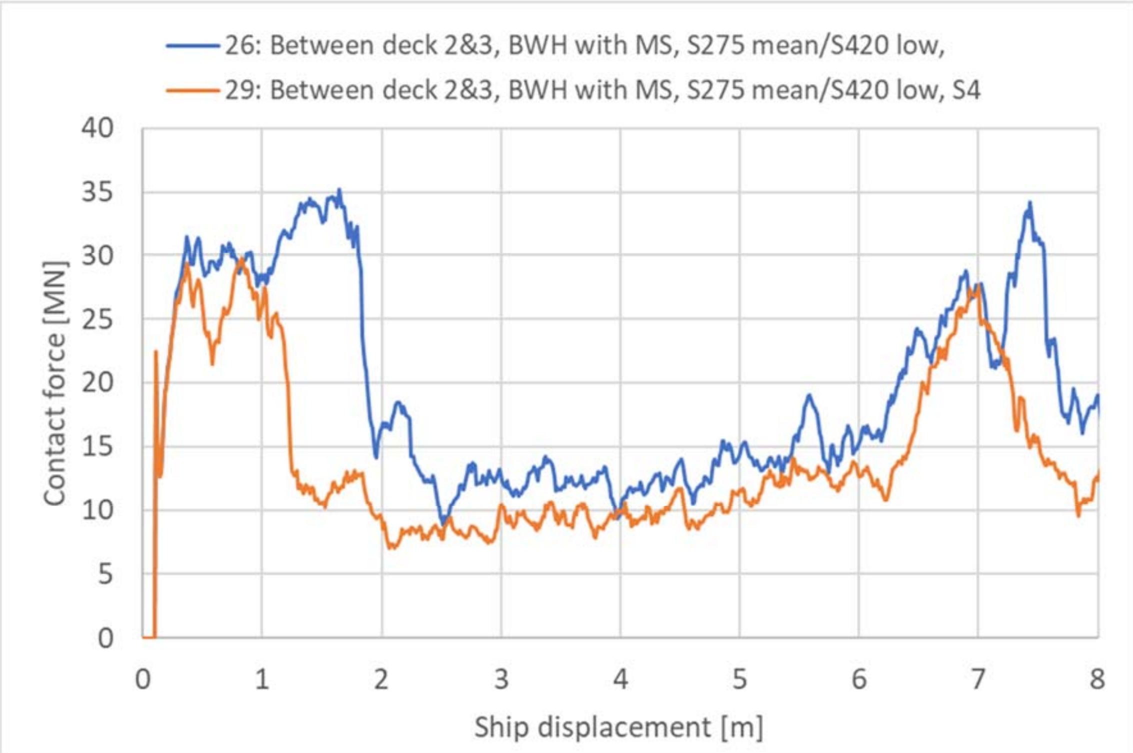
This section investigates the sensitivity of element type. The sensitivity is checked for impact between deck 2 and 3.

Figure 3-1 shows the force-displacement curves for simulation with full (S4 elements) or reduced (S4R elements) integration of the elements. Full integration displays lower force level. This follows the results in Appendix B section 3 [3]. A higher force level is generally conservative when studying ship impact for global assessment, see [5], justifying the results with reduced integration.

Figure 3-2 shows that lower energy is dissipated in both the deckhouse and the bridge girder when full integration is conducted. The proportion of energy dissipated in the bridge girder is also lower in the early stage of the impact with full integration, shown in Figure 3-4.

Figure 3-3 shows that the frictional dissipation is equal for full and reduced integration. Artificial energy is lower for the model with full integration as expected, shown in Figure 3-3. Of all simulations conducted, only the model with full integration displays low artificial energy, illustrated in Figure 3-5.

ID-no.	Max. contact force [MN] 0-8 m	Mean contact force [MN] 0-8 m
26	35	19
29	30	14



> *Figure 3-1 Contact force [MN] impact deckhouse-girder, sensitivity of element type*

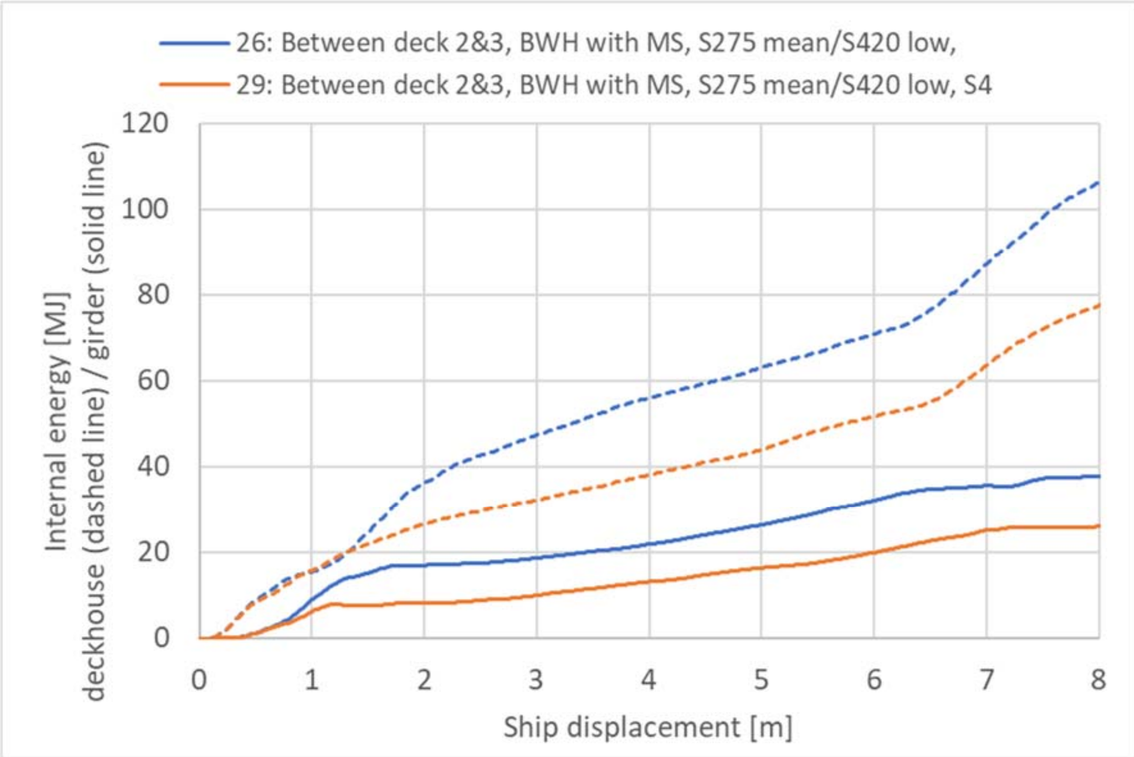


Figure 3-2 Internal energy [MJ] impact deckhouse-girder, sensitivity of element type

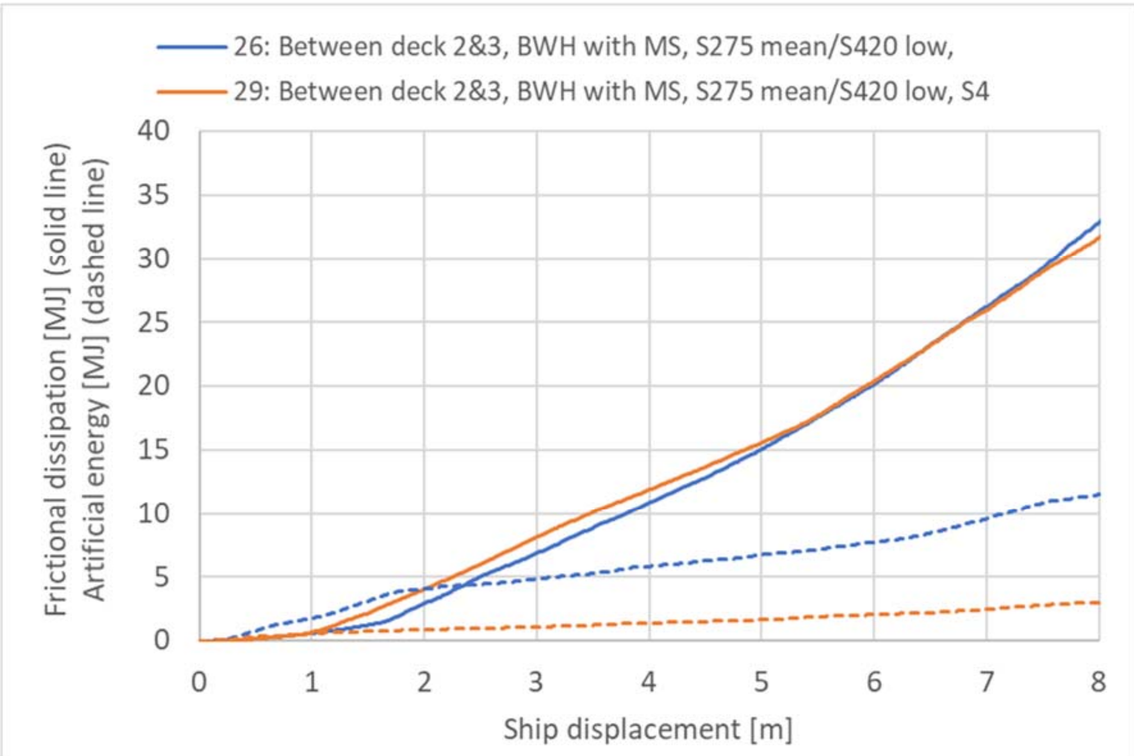
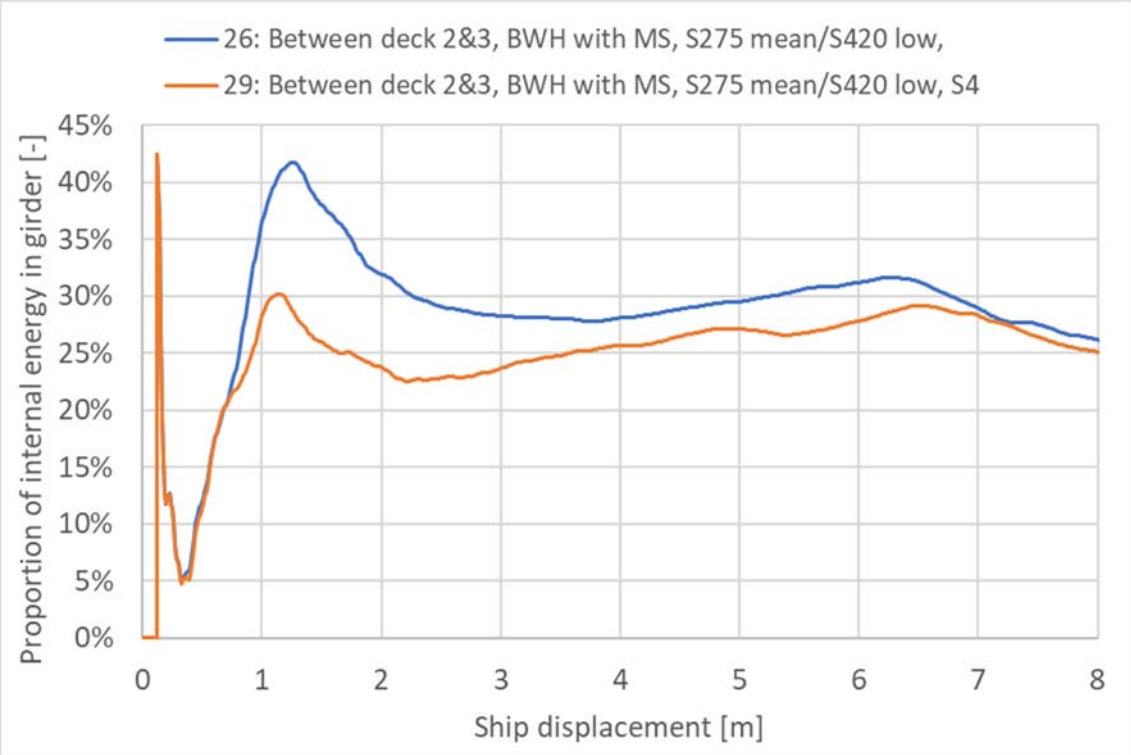
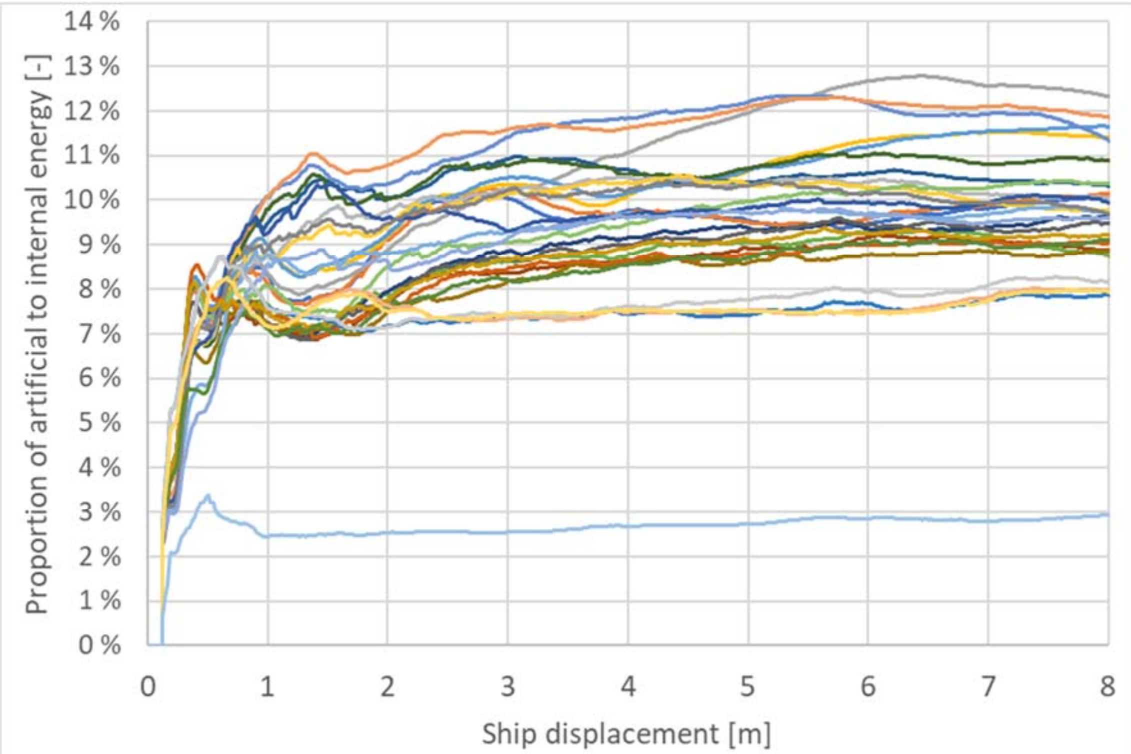


Figure 3-3 Frictional dissipation and artificial energy [MJ] impact deckhouse-girder, sensitivity of element type



> *Figure 3-4 Proportion of internal energy in girder [-] impact deckhouse-girder, sensitivity of element type*



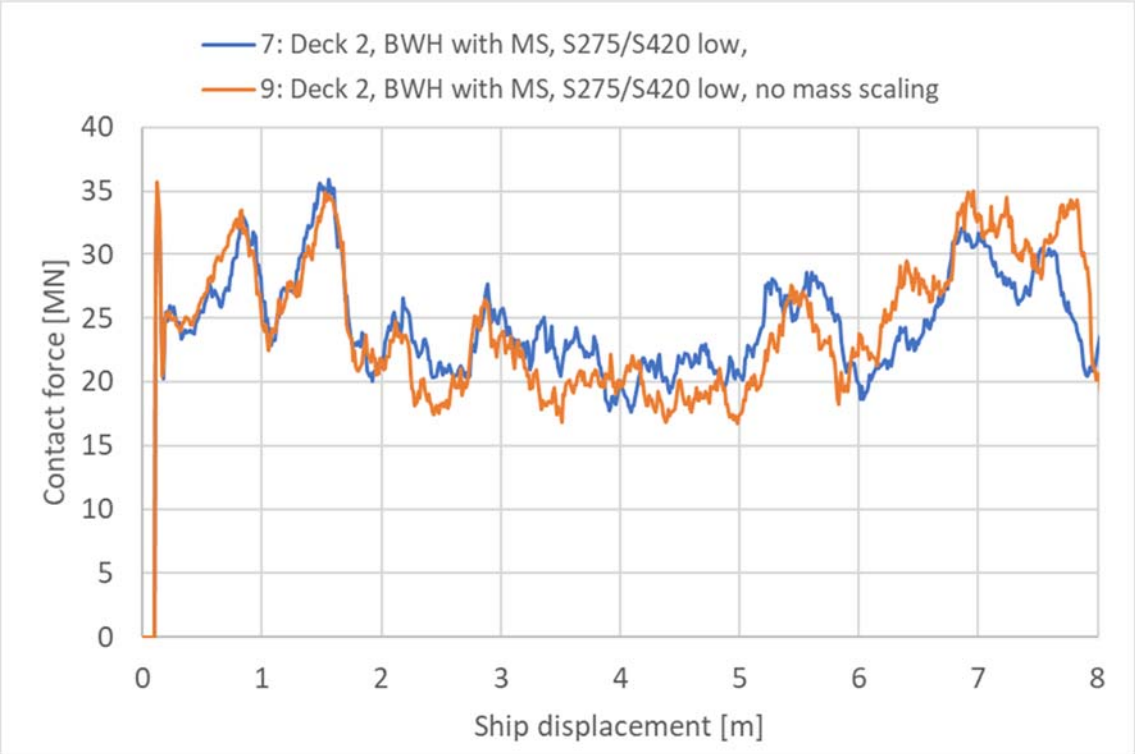
> *Figure 3-5 Proportion of artificial energy to internal energy [-] impact deckhouse-girder: The only low curve is with full integration*

4 SENSITIVITY OF MASS SCALING

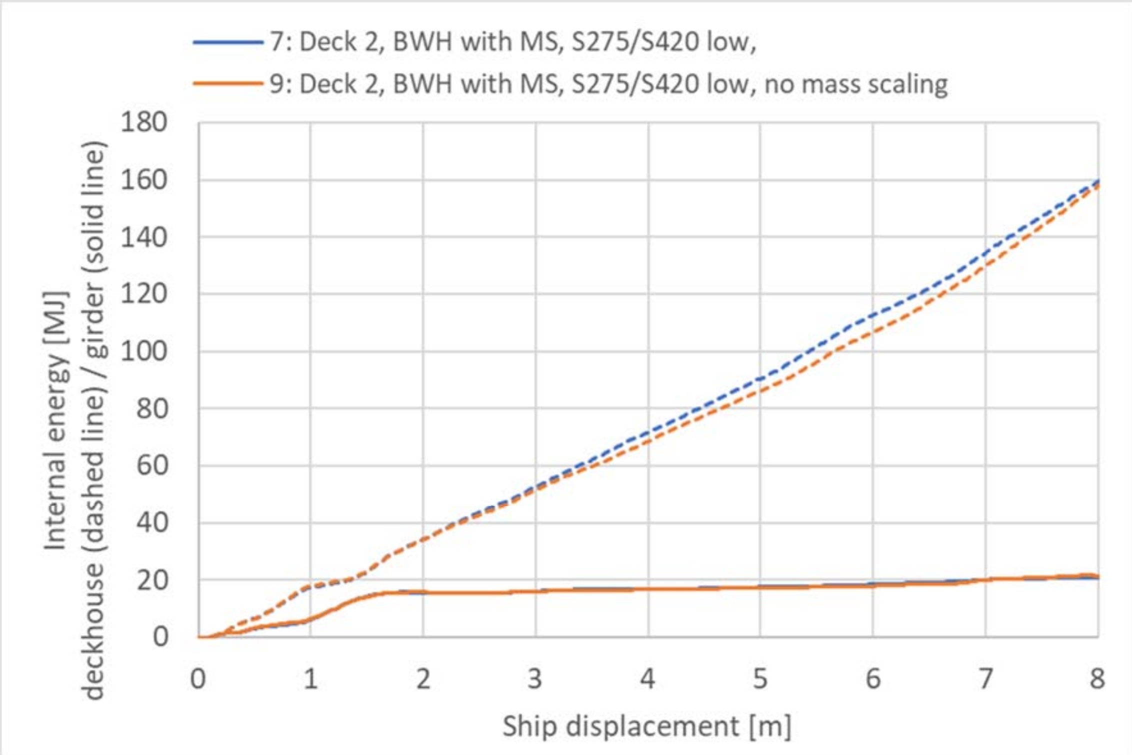
This section investigates the sensitivity of mass scaling. The sensitivity is checked for impact at deck 2.

Figure 4-1 to Figure 4-4 show that the local impact simulation is not very sensitive to mass scaling of the deckhouse ship. The differences are negligible, and the applied mass scaling is satisfactorily.

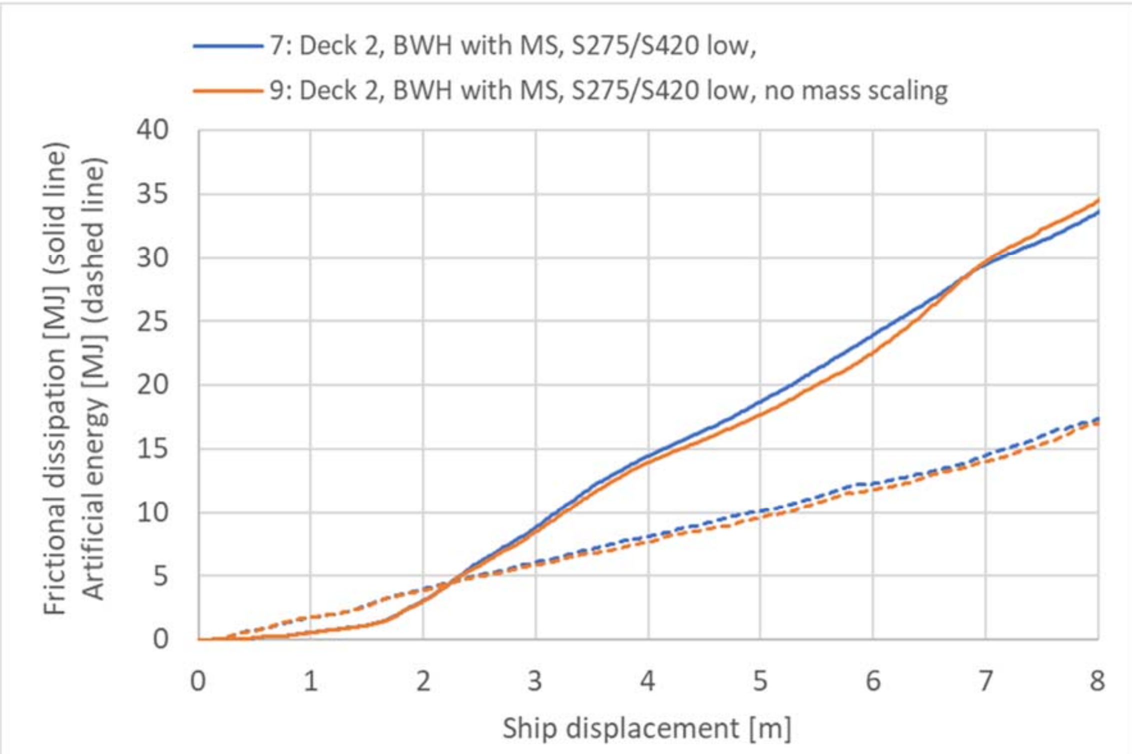
ID-no.	Max. contact force [MN] 0-8 m	Mean contact force [MN] 0-8 m
7	36	25
9	36	24



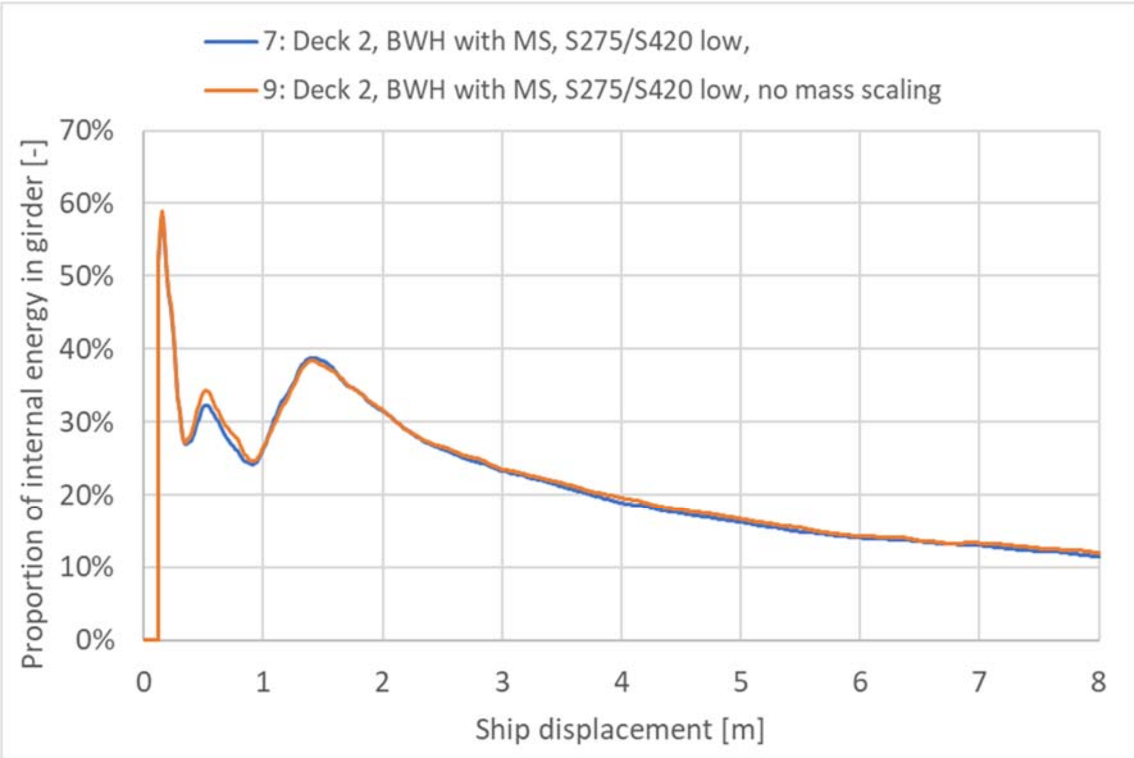
> *Figure 4-1 Contact force [MN] impact deckhouse-girder, sensitivity of mass scaling*



> *Figure 4-2 Internal energy [MJ] impact deckhouse-girder, sensitivity of mass scaling*



> *Figure 4-3 Frictional dissipation and artificial energy [MJ] impact deckhouse-girder, sensitivity of mass scaling*



> *Figure 4-4 Proportion of internal energy in girder [-] impact deckhouse-girder, sensitivity of mass scaling*

5 SENSITIVITY OF REINFORCED BRIDGE GIRDER

This section investigates the sensitivity of reinforced bridge girder cross section. The sensitivity is checked for impact at deck 2. The reinforced bridge girder cross section investigated has equal plate and stiffener thicknesses as the cross section in drawing no. SBJ-33-C5-OON-22-DR-006-A [6], i.e. the following thicknesses are changed:

- Plate thicknesses: 35 mm → 40 mm side walls
- Stiffeners: 8 mm →12 mm top, 16 mm → 20 mm side walls, 7 mm → 12 mm bottom

Figure 5-1 to Figure 5-4 show that the local impact simulation is a bit sensitive to the reinforced bridge girder cross section. Naturally, the force level becomes a bit higher, the internal energy in the deckhouse is higher and the amount of energy dissipated in the bridge girder is lower. The frictional dissipation becomes also lower for impact with the reinforced bridge girder because fracture is predicted earlier for the deckhouse elements.

ID-no.	Max. contact force [MN] 0-8 m	Mean contact force [MN] 0-8 m
24	45	31
30	47	36

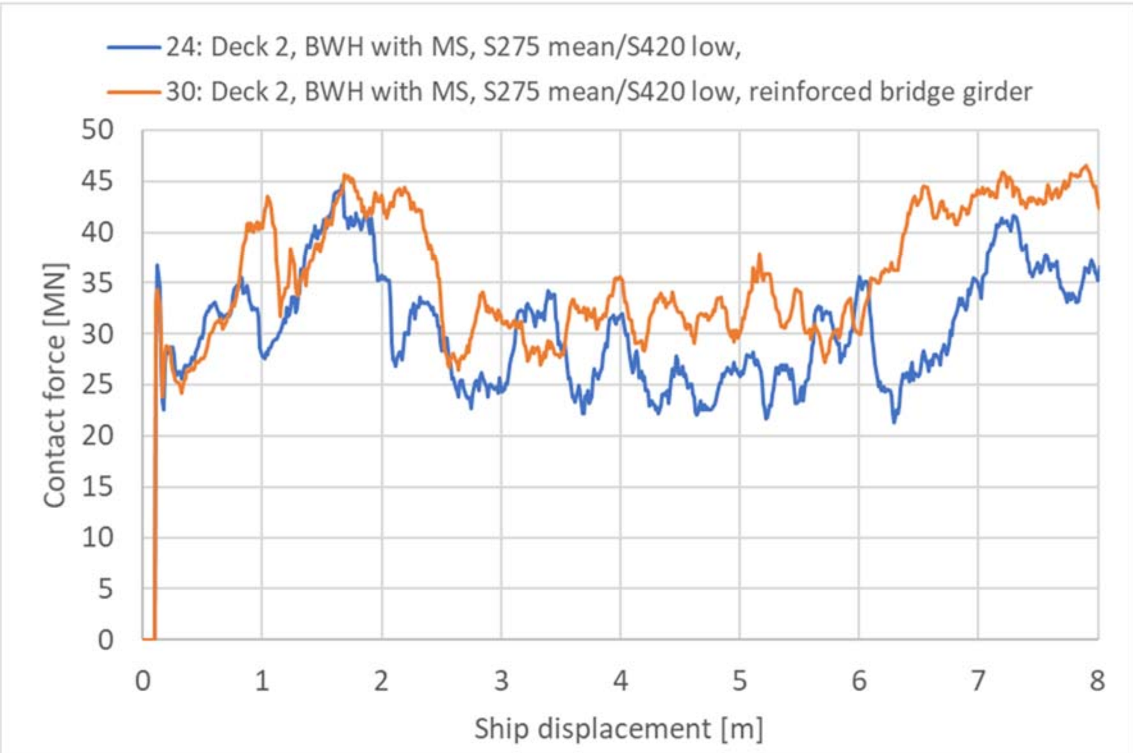
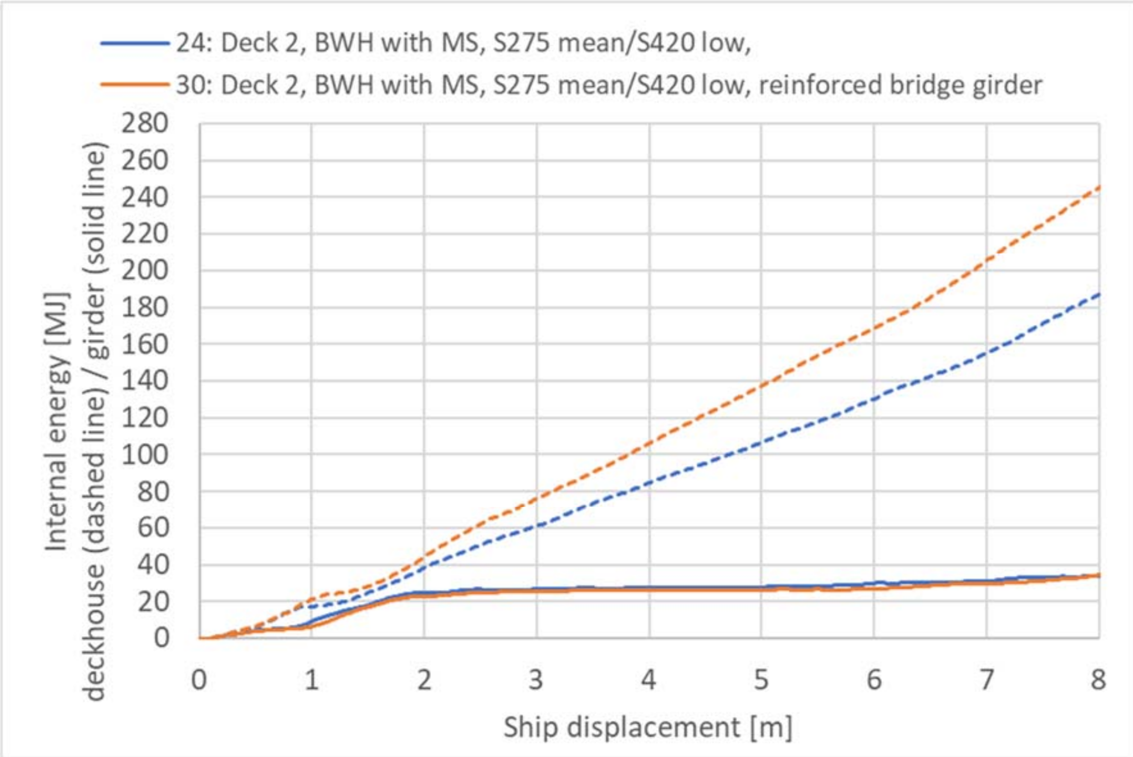
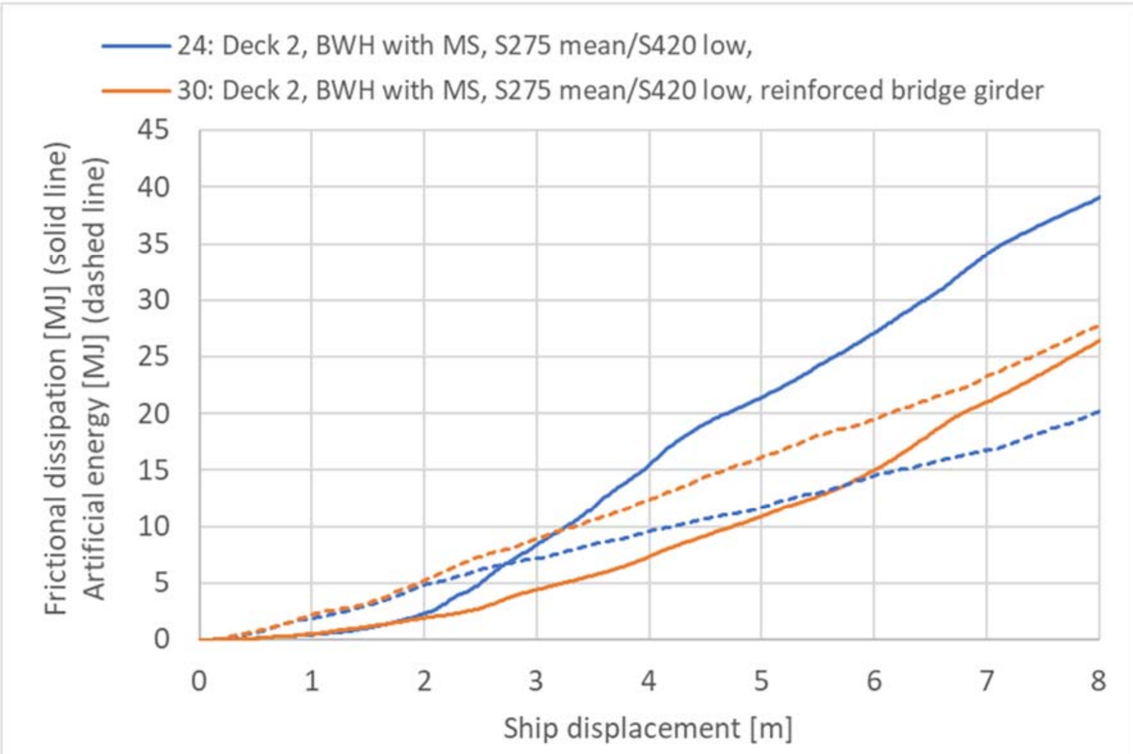


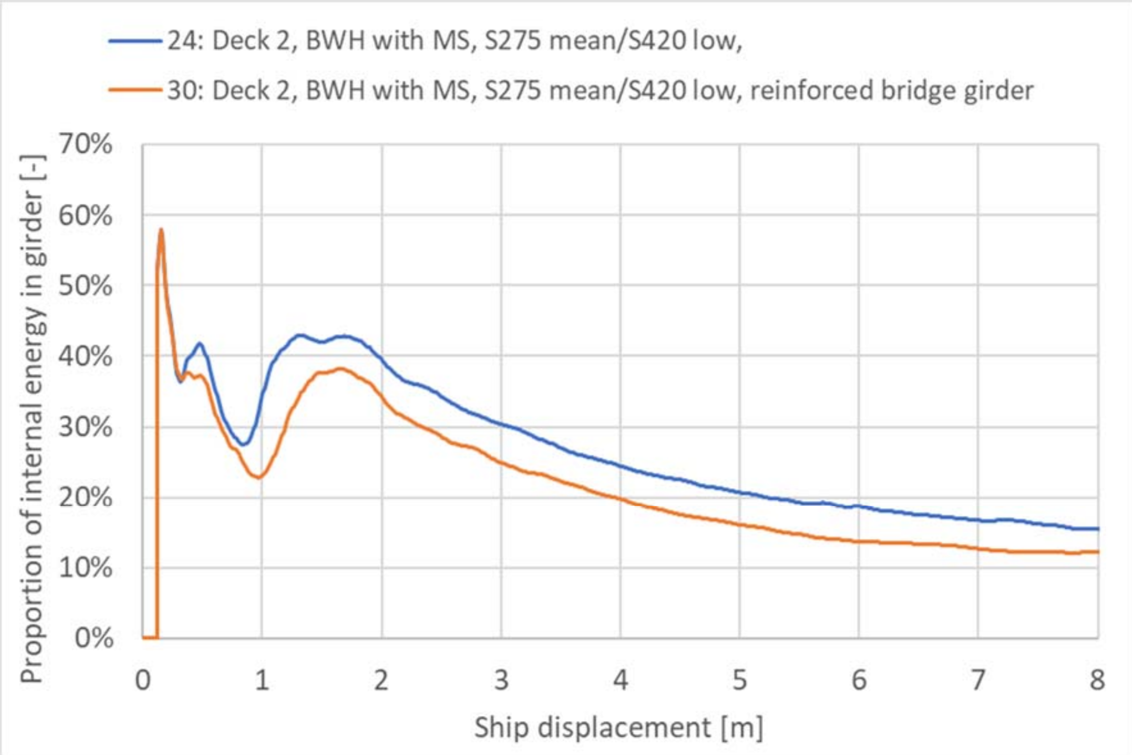
Figure 5-1 Contact force [MN] impact deckhouse-girder, sensitivity of girder cross section



> *Figure 5-2 Internal energy [MJ] impact deckhouse-girder, sensitivity of girder cross section*



> *Figure 5-3 Frictional dissipation and artificial energy [MJ] impact deckhouse-girder, sensitivity of girder cross section*

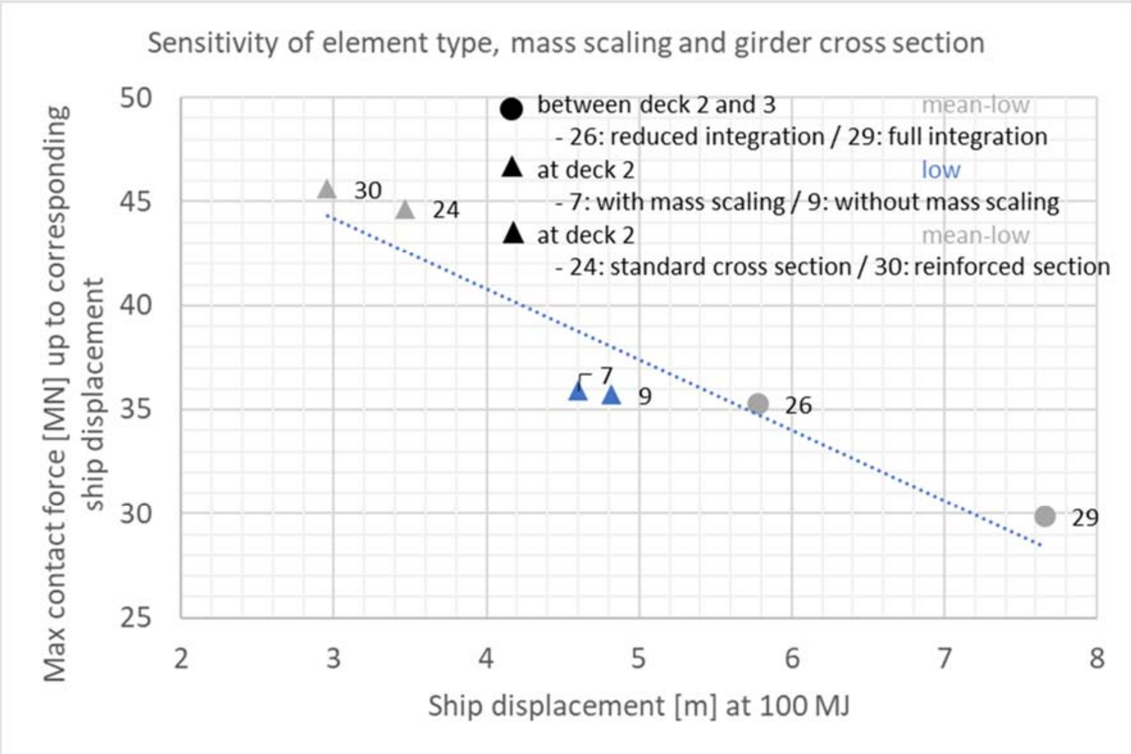


> *Figure 5-4 Proportion of internal energy in girder [-] impact deckhouse-girder, sensitivity of girder cross section*

Since the dissipated energy in the bridge girder is equal, it is concluded that the reinforced bridge girder is equally damaged as the non-reinforced bridge girder from the K7 bridge of phase 3. Higher dissipated energy in the deckhouse only means that the energy to be dissipated in the deckhouse-girder collision reaches 385 MJ earlier in the global assessment.

Figure 5-5 shows a graphical presentation of the sensitivity of element type, mass scaling and reinforced bridge girder cross section investigated. The maximum force from Figure 3-1, Figure 4-1 and Figure 5-1 is plotted, defined by a cut-off at ship displacement corresponding 100 MJ for the respective simulation.

The simulation is sensitive to the element type utilized and less sensitive to mass scaling and reinforced bridge girder cross section.



> *Figure 5-5 Sensitivity of element type, mass scaling and reinforced bridge girder cross section*

6 CONTROL OF ENERGY BALANCE

The energy balance for the simulations in this report is defined as:

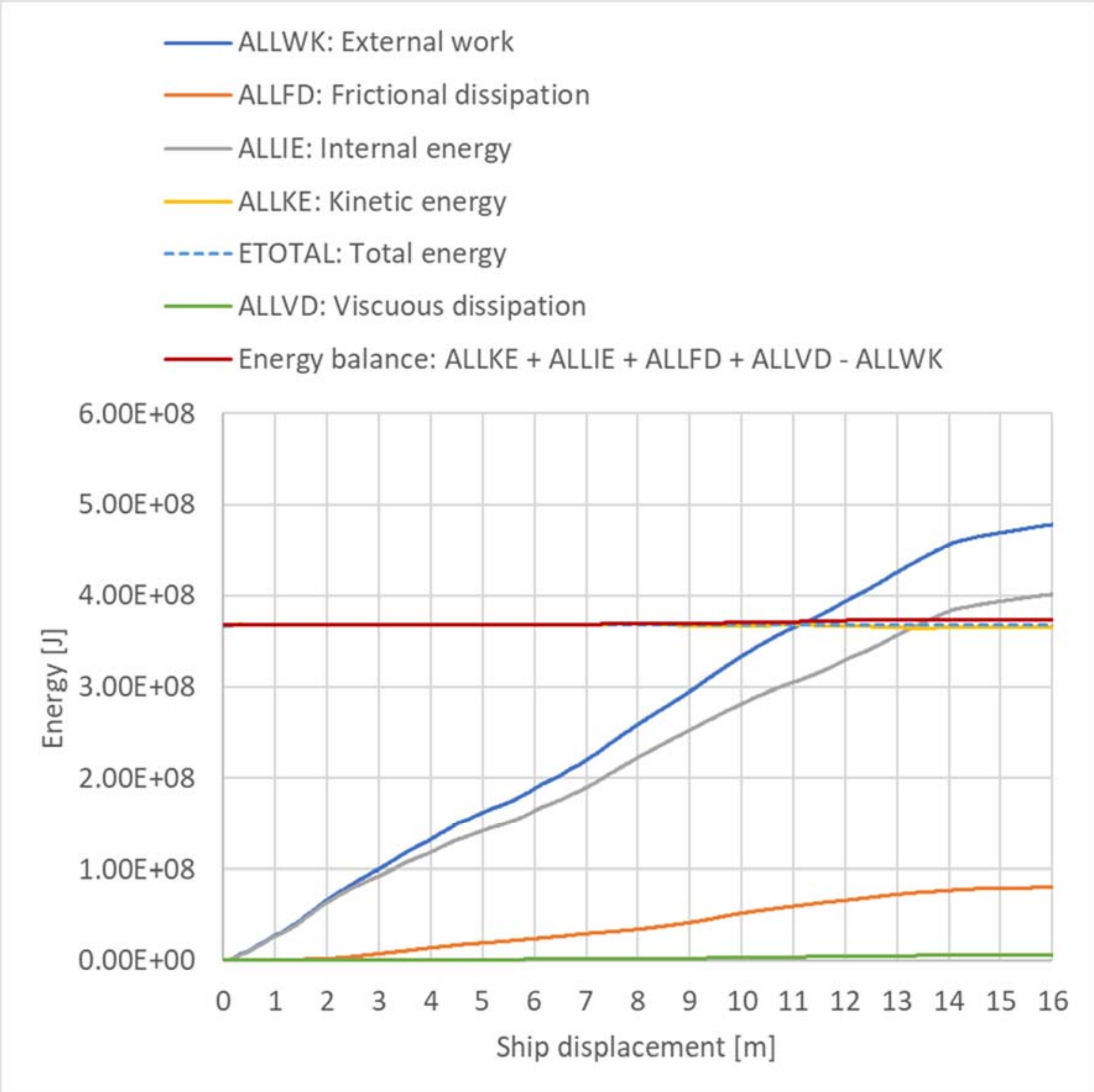
ETOTAL = ALLKE + ALLIE + ALLFD + ALLVD – ALLWK
Total energy = ("Kinetic" + "internal" + "frictional" + "viscous") energy - "external work"

Table 6-1 show the control of energy balance in the last frame (16 m ship displacement) for the selected models in section 5.3.2 [4]. Figure 6-1 to Figure 6-3 show the energy balance graphically.

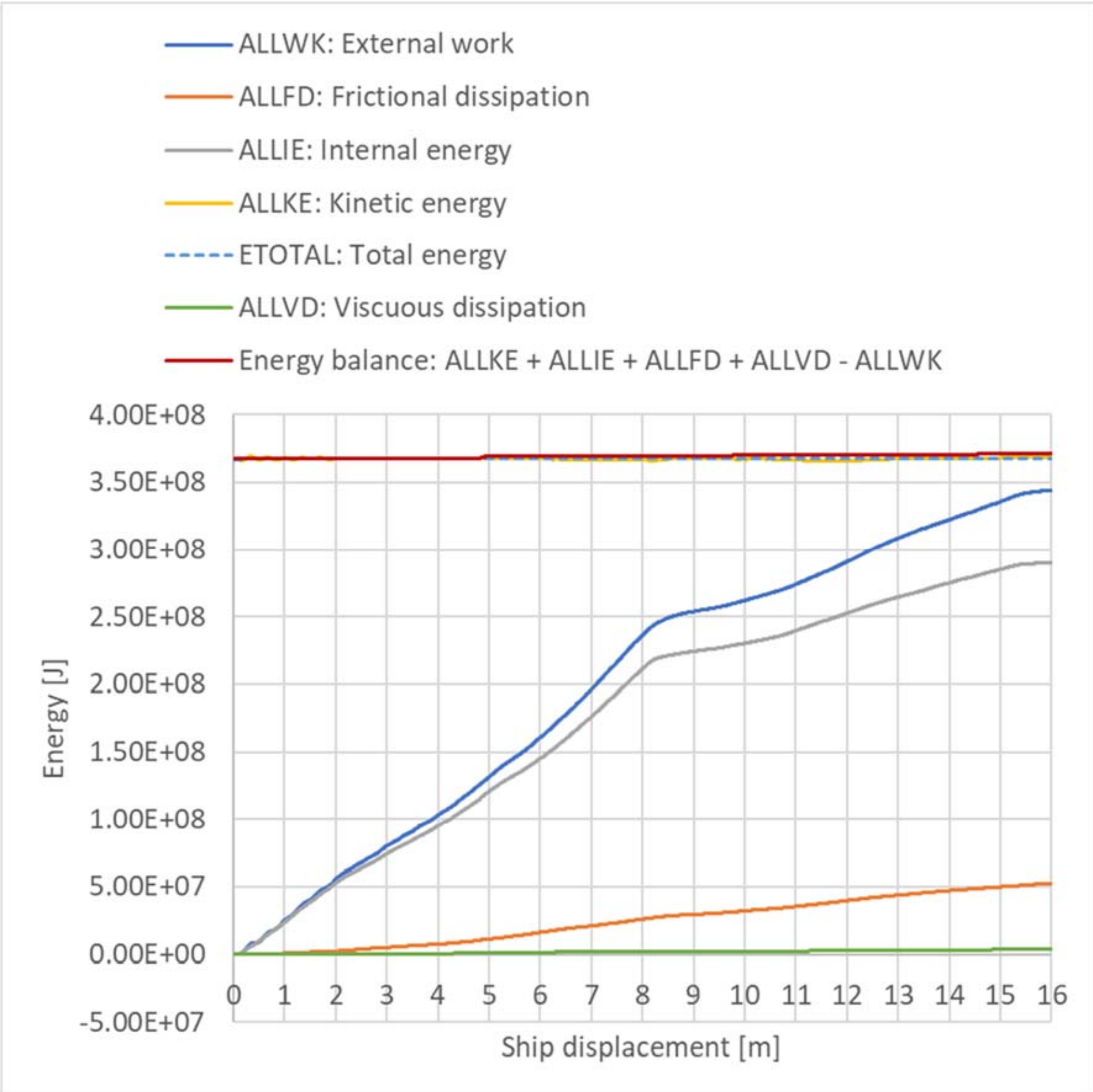
Default options to the explicit solver and sections control have been used, and the error in energy balance is satisfactorily low for the results displayed.

> *Table 6-1 Energy balance of the models reported in section 5.3.2 [4]*

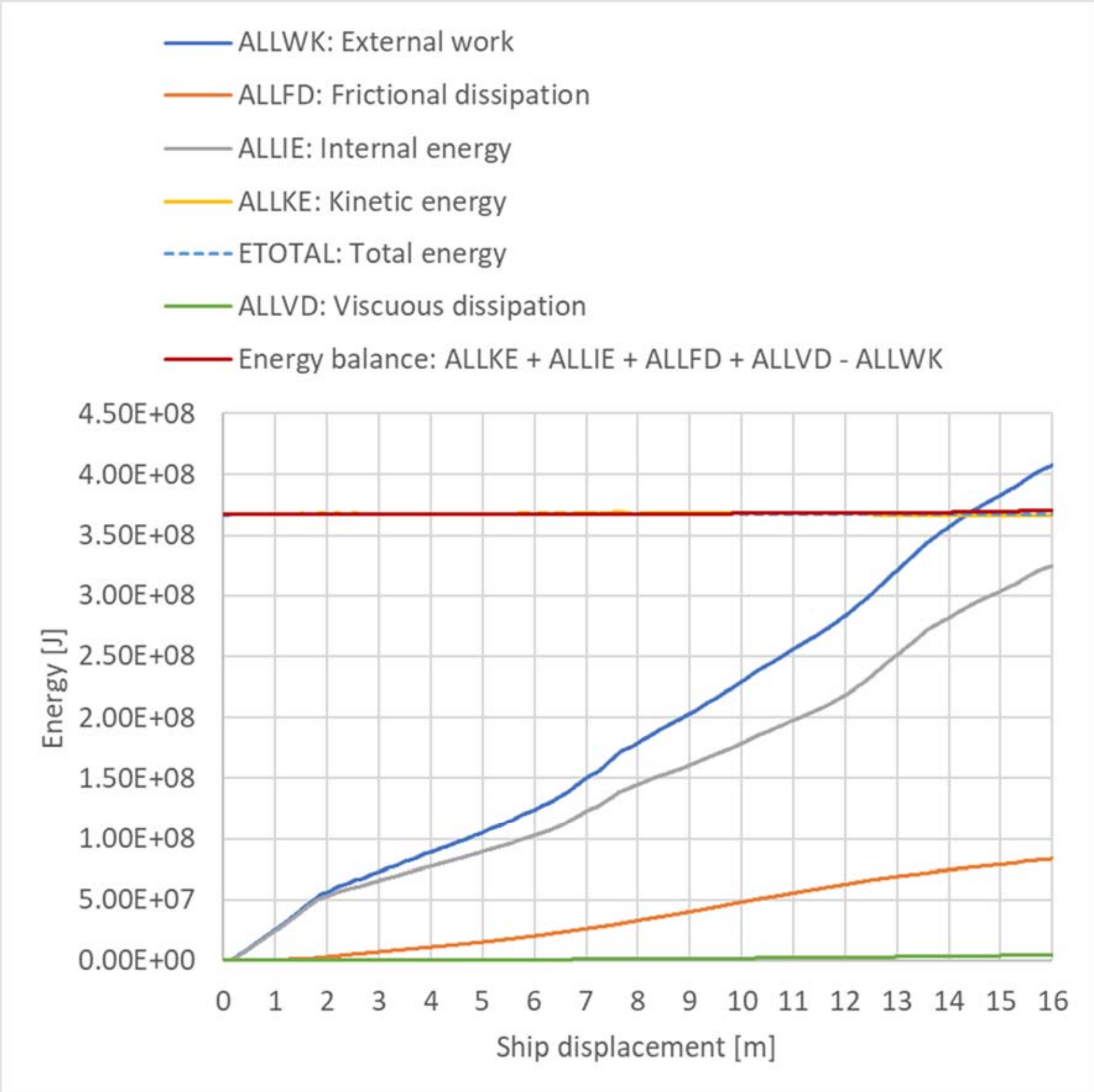
Ship impact model	At deck 2	Inclined at deck 4	Between deck 2 and 3
ALLKE	365 MJ	369 MJ	366 MJ
ALLIE	403 MJ	290 MJ	328 MJ
ALLFD	81 MJ	53 MJ	84 MJ
ALLVD	6 MJ	4 MJ	5 MJ
ALLWK	480 MJ	345 MJ	412 MJ
ETOTAL	368 MJ	368 MJ	368 MJ
ALLKE + ALLIE + ALLFD + ALLVD - ALLWK	374 MJ	372 MJ	371 MJ
Error	1.7 %	1.0 %	0.9 %
Energy balance ok?	Yes	Yes	Yes



> *Figure 6-1 Energy balance of model with ID-no. 31: Impact at deck 2*



> *Figure 6-2 Energy balance of model with ID-no. 32: Impact inclined at deck 4*

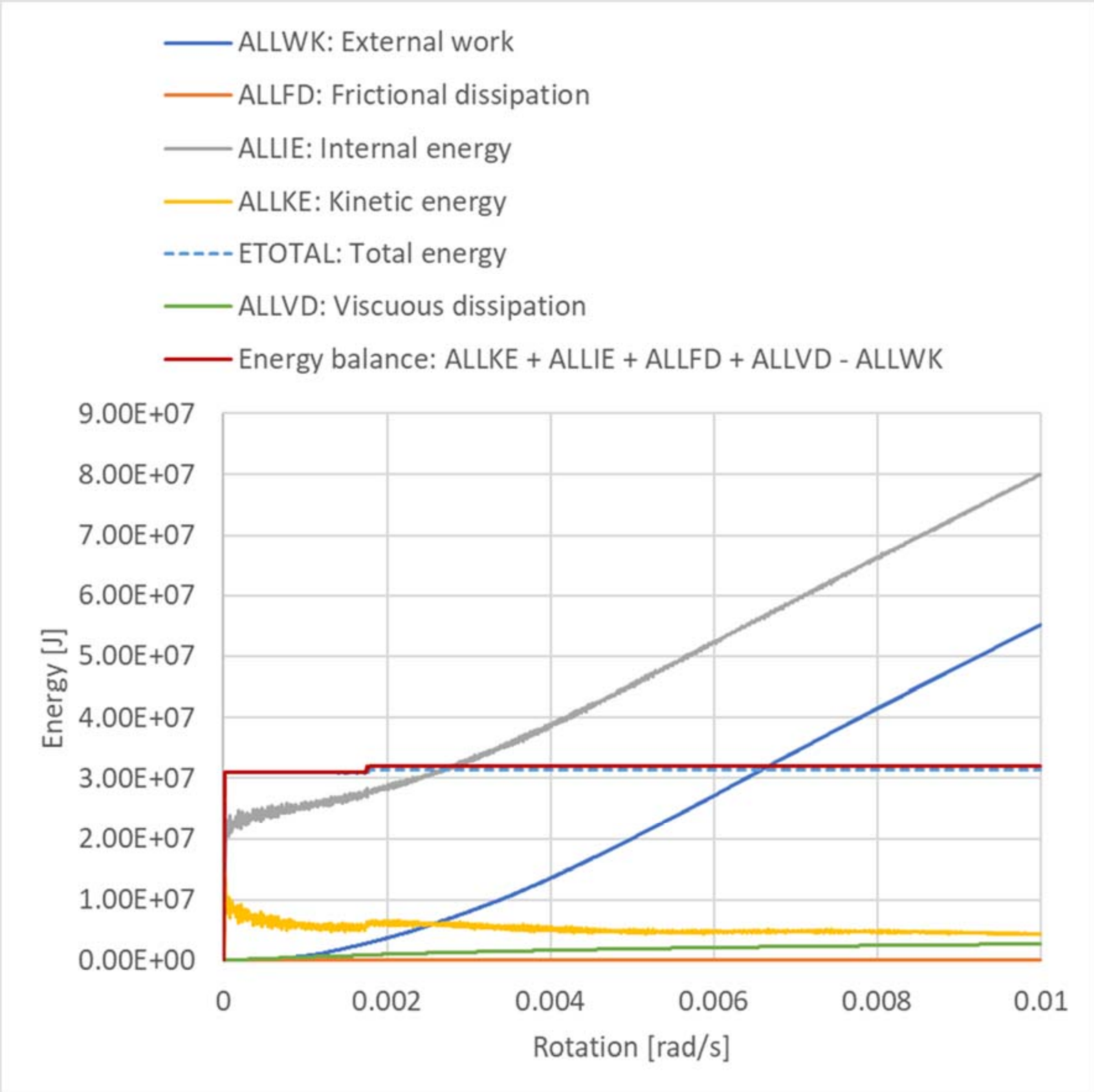


> *Figure 6-3 Energy balance of model with ID-no. 28: Impact between deck 2 and 3*

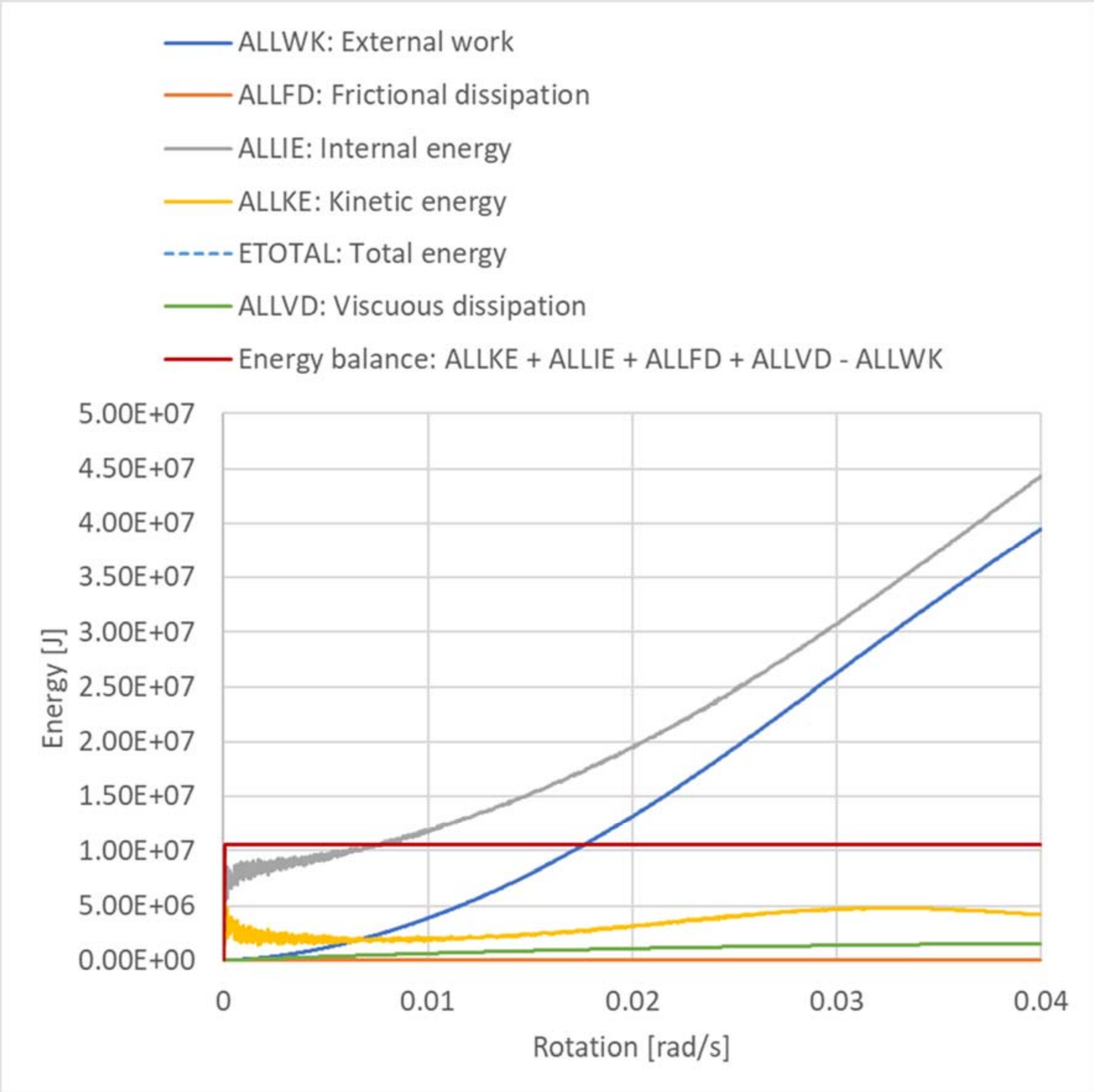
Table 6-2 shows the control of energy balance in the last frame for selected residual capacity models evaluated with the explicit solver in section 5.3.3 [4]. Figure 6-4 and Figure 6-5 show the energy balance graphically. The error in energy balance is satisfactorily low.

> *Table 6-2 Energy balance for selected models reported in section 5.3.3 [4]*

Residual capacity model	Moment about strong axis, damaged girder at 16 m ship displacement	Moment about weak axis, damaged girder at 16 m ship displacement
ALLKE	4 MJ	4 MJ
ALLIE	80 MJ	44 MJ
ALLFD	0 MJ	0 MJ
ALLVD	3 MJ	2 MJ
ALLWK	55 MJ	39 MJ
ETOTAL	31 MJ	11 MJ
ALLKE + ALLIE + ALLFD + ALLVD - ALLWK	32 MJ	11 MJ
Error	2.1 %	0.2 %
Energy balance ok?	Yes	Yes



> *Figure 6-4 Energy balance of residual capacity model: Moment about strong axis, damaged girder at 16 m ship displacement*



> *Figure 6-5 Energy balance of residual capacity model: Moment about weak axis, damaged girder at 16 m ship displacement*

7 REFERENCES

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