Semi-submersible structural design

Strength and fatigue assessment of a twin-pontoon semi-submersible with different bracing configurations

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1 Project objectives

Bracing configurations

Semi-submersibles are common vessels in the offshore sector, such as the drilling market as shown in Figure 1. These vessels usually have a bracing structure to restrain floater movement and to support the deckbox structure. The bracing configuration influences strength, fatigue and other semi-submersible parameters, such as payload, structural vertical centre of gravity (VCG) and redundancy. No references regarding semi-submersible design motivation were found during the literature review [1]. Semi-submersible designers do not state why their design is advantageous with respect to payload, redundancy, strength or fatigue. For example, adding vertical diagonal bracings for the semi-submersible depicted in Figure 1 reduces stress in columns and deckbox, therefore plating can be reduced at certain areas, but by how much? The first objective was therefore to study the structural design of a semi-submersible when applying different bracing configurations. The different bracing configurations are compared based on total structural weight, structural VCG, payload, structural redundancy and fatigue. From which rules of thumb can be derived.

Figure 1: Semi-submersible drilling platform ‘Shen Lan Tan Suo’ [2]

Fatigue resistance similarity

Fatigue resistance is usually determined by S-N curves for specific structural details, in which the stress range is plotted against the number of cycles. These S-N curves are mostly based on fatigue tests of welded joints at small scale, also known as small-scale specimen (SSS). Large-scale specimen (LSS) and full-scale specimen (FSS) fatigue tests are performed less frequent. Regarding semi-submersibles, if the bracings and columns are tubular members, fatigue resistance of the brace-column and brace-brace connection is typically based on LSS tubular joint fatigue tests.

The literature review partly focused on fatigue resistance similarity between SSS planar joints and LSS tubular joints using the hot spot stress as fatigue assessment concept. The scatter of the fatigue resistance data was considered large, therefore similarity seemed lacking. This may be due to residual stress and local notch effects not accounted for by the hot spot stress concept, differences in load-carrying and non-load-carrying joints, thickness differences between specimens and different stress ratios. Also, differences in load paths, number of hot spots and residual stresses between SSS and LSS may result in divergent fatigue resistance. In previous studies [3] [4], an increase in similarity between SSS planar joints was demonstrated by the average effective notch stress method. Since the average effective notch stress concept includes more information regarding geometry and loading & response compared to the hot spot stress concept, it is expected that similarity between SSS planar joints and LSS tubular joints increases as well. If fatigue resistance similarity is proven between SSS planar joints and LSS tubular joints, a design S-N curve based on many SSS planar joints can then be used for tubular joints. Such as tubular brace-column connections.

Fatigue assessment

The fatigue limit state (FLS) of semi-submersibles remains a challenge in today’s practice [1]. Service cracks are frequently found in semi-submersibles during inspections, especially at the fatigue sensitive brace-column and brace-brace connections. These locations are critical with respect to the FLS due to geometric stress intensities, resulting from change in structure stiffness and discontinuity. Moreover, welded joints introduce stress intensities due to welding defects, notched geometry and stiffness changes.

Since marine and offshore structures, such as semi-submersibles, increasingly operate in remote areas [2], the demand to accurately estimate the fatigue damage increases as well. Therefore, the final objective is to perform a detailed fatigue assessment by state-of-the-art fatigue assessment concepts.

2 Methods and results

Bracing configurations

The influence of bracings on characteristic responses, defined as loading and accelerations governing for the strength and fatigue of semi-submersibles, was studied first. Generally, an increase in bracing diameter results in an increase in characteristic response. However, bracings do not affect characteristic responses much, as differences below 11% are observed. Global strength assessments in the ultimate and accidental limit states were performed using FEA for different bracing configurations, see Figure 2 as example and Figure 3 for the studied bracing configurations. Each bracing configuration differentiates itself being beneficial for certain load cases, or is beneficial regarding fatigue sensitive locations. The structural design of semi-submersibles with different bracing configurations were modified to have similar structural performance compared to the reference semi-submersible. The bracing configurations were evaluated based on payload, structural centre of gravity, structural redundancy and fatigue. An overview of the bracing configuration ranking is provided in Table 1. $\Delta_{payload}$ and Δ_{VCG} are defined as payload and structural VCG differences with respect to the reference semi-submersible. Structural redundancy is mainly evaluated by the difference in number of bracing members, $\Delta_{\#bracings}$, where an increase in number of bracings is favourable. Fatigue is mainly evaluated by welding volume at identified fatigue sensitive locations, where a negative welding volume difference, Δ_{Vweld}, is advantageous. Generally, the presence of transverse horizontal bracings affects the structural performance most significantly, since a payload reduction of 22% is observed when not present due to the dominant splitting force load case and ineffective load path. Adding diagonal bracings in the horizontal or vertical plane, reduces column and deckbox loading for the longitudinal shear, torsion moment and inertia load cases, resulting in a payload increase up to 5%. Omitting braces results in the lowest amount of fatigue sensitive locations. However, since the columns and deckbox structure needs strengthening, welding volume at other fatigue sensitive locations increases, which affects fatigue negatively. The bracing configuration selection should be merely based on the semi-submersible's requirements. Therefore, the designer should first rank the requirements after which a bracing configuration can be designed.

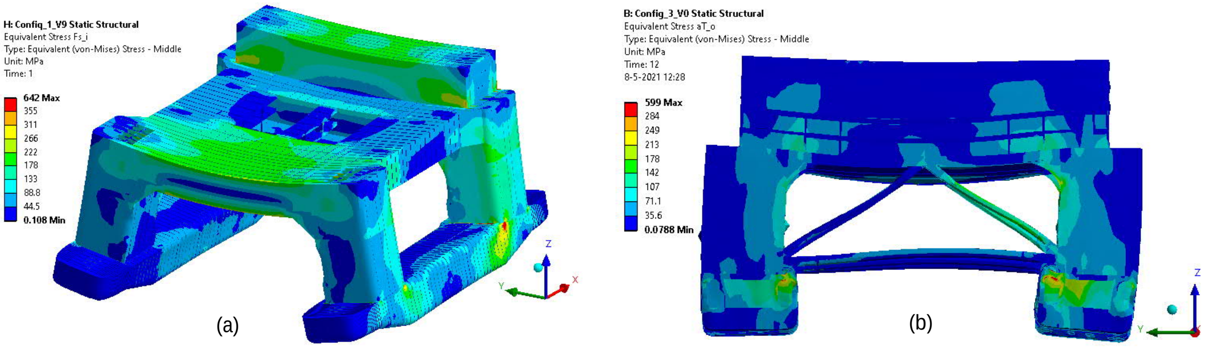

Figure 2: Equivalent stress plots of configuration 1 splitting force load case (a) and configuration 3.1 transverse acceleration load case (b)

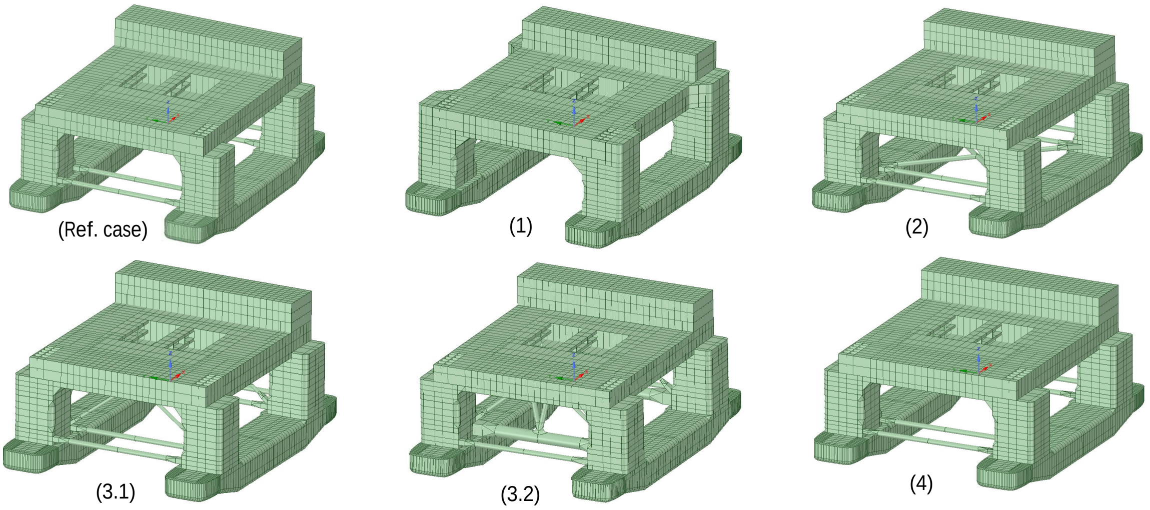

Figure 3: Bracing configurations

Table 1: Ranking bracing configurations

Ranking	Payload		Structural VCG		Structural redundancy		Fatigue	
	Config.	$\Delta_{payload}$	Config.	Δ_{VCG}	Config.	$\Delta_{\#bracings}$ [-]	Config.	Δ_{Vweld} [dm^3]
1	3.2	+5%	3.2	-4%	3.2	8	3.1	-45
2	2	+4%	2	-2%	3.1	4	Ref. case	0
3	3.1	+1%	4	0%	2	2	4	+28
4	Ref. case	0%	3.1	0%	4	0	2	+35
5	4	-2%	Ref. case	0%	Ref. case	0	1	+73
6	1	-22%	1	+7%	1	-4	3.2	+867

Fatigue resistance similarity

Fatigue resistance data of SSS planar joint specimens were provided by the TU Delft. Five LSS tubular joints with differences in geometry and boundary conditions were studied by shell FEA and volume FEA. LSS tubular joint fatigue test information was derived from literature, where the tubular and weld geometry, boundary conditions and fatigue lifetime was reported, see Figure 4 as example.

Including weld geometry in shell FEA results in better agreement of the structural stress compared to volume FEA, since chord local bending moments are more accurate. The significance of including weld geometry increases by larger weld size. Also, it is observed that including weld geometry can result in different global stress flow. The studied LSS tubular joints demonstrate not including weld geometry in shell FEA can overestimate bending stress up to 208%.

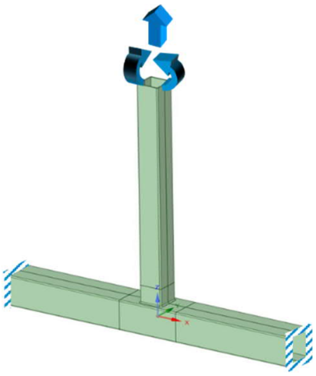

Figure 4: LSS tubular square hollow section (SHS) T-joint

The average effective notch stress of LSS tubular joints was computed through weld toe notch stress integration. The through thickness weld toe notch stress distributions, based on shell FEA structural stress, were verified by detailed volume FEA, see Figure 5 as example. Compared to the hot spot stress concept, LSS tubular joint fatigue resistance similarity with respect to SSS planar joints has increased for the average effective notch stress concept. Shown by Figure 6, most LSS tubular joints fit inside the average effective notch stress SSS planar joint data. For divergent LSS tubular joints, dissimilarity is most likely linked to differences in actual and interpreted specimen boundary conditions and weld geometries. Fatigue resistance similarity, expressed as the strength scatter index, $T_{\sigma S}$, and intercept, $\log_{10}(C)$, of LSS tubular joints is increased compared to hot spot fatigue resistance, see Table 2. Differences in slope m are similar, therefore similarity between SSS planar joints and LSS tubular joints is comparable to that respect. More LSS tubular joints should be studied to demonstrate similarity with higher confidence, shown by CLB and CUB.

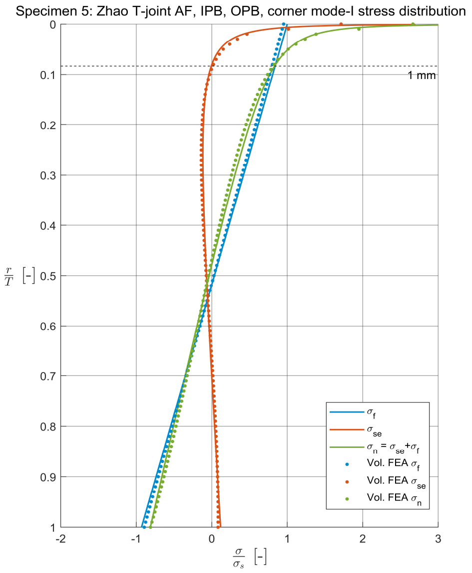

Figure 5: Weld toe notch stress distribution (σ_n) LSS tubular SHS T-joint

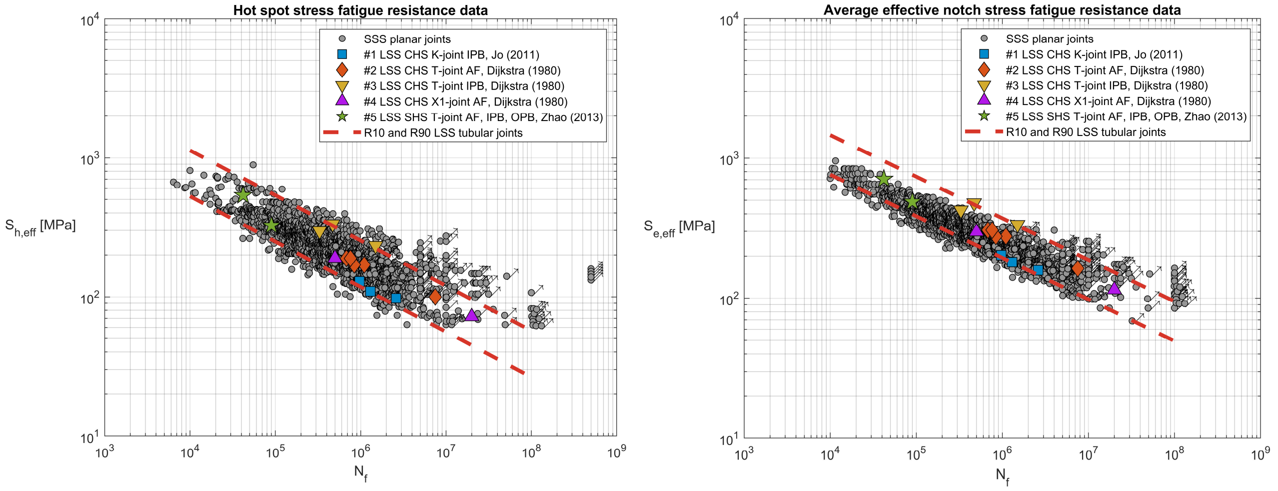

Figure 6: Hot spot (a) and average effective notch stress (b) fatigue resistance data

Table 2: Fatigue resistance similarity comparison

Similarity indicator	Specimen	Hot spot stress concept			Average effective notch stress concept		
		C95LB	μ	C95UB	C95LB	μ	C95UB
$T_{\sigma S}$	SSS planar joints LSS tubular joints	-	1 : 2.18 1 : 2.15	-	-	1 : 1.64 1 : 1.91	-
$\log_{10}(C)$	SSS planar joints LSS tubular joints	13.13 12.27	13.86 12.89	14.58 13.52	14.44 13.61	14.94 14.19	15.43 14.76
m	SSS planar joints LSS tubular joints	3.21 2.81	3.51 3.08	3.83 3.36	3.57 3.13	3.76 3.37	3.98 3.61

Fatigue assessment

To accurately estimate fatigue lifetime, a detailed fatigue assessment is performed of the tubular brace-brace connection of bracing configuration 2. At global level, bracings are mainly loaded by axial forcing for most wave frequencies and headings. At local level, i.e. at the tubular joint, multi-axial loading is present around the circumference. However, at the critical saddle location, mode-I stress dominates. Therefore, multi-axial fatigue is not considered. The structural stress [5], S_s, average effective notch stress [4], S_e, and hot spot stress [6], S_h, were applied as fatigue assessment concepts. A complex tubular CHS X-joint was designed with internal ring-stiffeners based on a parametric study. Fatigue damages were calculated as D_s = 0.63, D_e = 0.28 and D_h = 0.45, thus acceptable. Compared to common fatigue assessment concepts, the detailed S_s and S_e fatigue assessments reduce the possibility of service cracks and maintenance and inspection work can be planned more precise. However, DNV-GL and IIW guidelines state a fatigue resistance slope change is present above 10^7 cycles (N), which is not accounted for in S_s and S_e. To study the presence of a slope change and to possibly establish a more accurate fatigue damage estimation for S_s and S_e, a recommendation for further research is to include more fatigue tests for $N > 10^7$, from which a design S-N curve can be derived.

3 Relevance

Bracing configurations

The study of different bracing configurations demonstrates the neglectable local bracing loading on global semi-submersible loading and responses. This conclusion provides an approach for future conceptual designs of semi-submersibles, where deriving global water loading solely by splitting forces is sufficient. The performed FEA of different bracing configurations shows the impact on structural performance of a twin-pontoon semi-submersible, from which rules of thumb can be derived for future conceptual designs of semi-submersibles.

Fatigue resistance similarity

By assessing fatigue resistance by the more detailed average effective notch stress concept, fatigue resistance similarity between SSS planar joints and LSS tubular joints has increased. This was previously only concluded for SSS planar joints. A SSS planar joint based design S-N curve is therefore applicable for tubular fatigue sensitive locations of semi-submersibles and other structures and increases the applicability of the average effective notch stress as fatigue assessment concept. Compared to the hot spot stress concept, the reduced scatter increases the fatigue damage accuracy.

Fatigue assessment

The fatigue damage of a semi-submersible brace-brace was assessed by state-of-the-art fatigue assessment concepts. The fatigue assessment provides an approach to determine fatigue damage estimation in a more detailed manner. This reduces the possibility of service cracks for marine and offshore structures, which increasingly operate in remote areas.

4 References

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