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COMPARATIVE FATIGUE STREGTH ANALYSIS FOR A CONTAINER SHIP WITH INITIAL AND OPTIMIZED STRUCTURE, UNDER IRREGULAR WAVE LOADS

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ABSTRACT

This study is focused on the long term fatigue strength analysis of ship structures under irregular wave loads, taking into account the oscillations and the vibrations ship hydroelastic response influence. The fatigue assessment is based on the cumulative damage factor Palmgren-Miner method, considering the irregular sea long term description by World Wide Trade wave significant height histogram. The study is carried out on an 1100 TEU container ship, with total length of 173.42 m, speed 18 knots, for initial and optimized structure, on full cargo and intermediate cargo, without containers on deck, loading cases. The short term significant stresses for fatigue assessment are obtained by linear and non-linear hydroelastic ship response analysis, combined with stress hot-spots by 3D/1D-FEM global-local strength analysis. The 1D-FEM strength, the short term dynamic and long term fatigue numerical analyses are carried out with own program codes, and the 3D-FEM strength analysis by SolidWorks program and own user subroutines. The short term strength analysis points out that the deck panels are the higher container ship structural risk domains and the optimized case is more sensitive to the fatigue.

KEYWORDS: fatigue, optimized structure, hydroelasticity, container ship

1. INTRODUCTION

In advanced ship design rules [3],[9], [10] is required the evaluation of ship service life starting from the early design steps, on the initial ship hull structure design concept, making possible to carry out several assessment during the design process.

In this study, the numerical analysis are carried out on an 1100 TEU container ship, considering the initial structure, from the first draft based on Germanischer Lloyd Poseidon program [10], and the optimized structure, under the minimum weight criteria and satisfying strength admissible and buckling criteria. The ship is considered under full cargo and intermediate, without containers on deck, loading case conditions. The external head waves loads are considered as equivalent quasi-static for stress hot-spots evaluation and irregular waves with second order interference components for hydroelastic short term dynamic response.

The main characteristics of the 1100 TEU container ship are presented in section 2.

In section 3 are presented the numerical results for global-local strength analysis, based on 1D – equivalent girder and 3D–FEM global-local models.

The stress results from section 3 make possible to obtain the higher risk structural domains, the stress hot-spots and the 3D/1D stress correlation factors, for the container ship structure.

Usually the fatigue analysis based on rules [9] are taking into account only the low frequencies oscillations wave induced ship dynamic response [1]. In the case of ships with length over 150 m the higher frequencies vibration response become significant and have to be considered for the fatigue analysis [5]. In section 4 the container ship hull dynamic response induced by waves is obtained, in the hypotheses of the linear and non-linear hydroelasticity theory, including besides oscillations also springing and whipping steady state and transitory global vibration responses [2], [4], [6], [11], [15].

In section 5 is presented the long term fatigue analysis for the container ship initial and optimized structure, based on the Palmgren-Miner cumulative damage ratio method [3],[7],[9],[14],steel S-N fatigue design curves and long term World Wide Trade wave significant height histogram. In section 5, the results from section 3 and 4 are combined.

Section 6 includes the conclusions of this study, pointing out the differences between initial and optimized structure, with or without vibration components, on fatigue.

2. THE 1100 TEU CONTAINER SHIP DATA

This study is carried out for a general cargo 1100 TEU container ship, with five cargo holds and two rows of cargo hatches. The main dimensions of the container ship are presented in Table 1.

Table 1. The main dimensions of 1100 TEU container

Type of ship	Container ship
Hull type	Mono-hull
Overall length L_{OL} [m]	173.42
Length between perpendiculars L_{pp} [m]	164
Breadth moulded, B_{max} [m]	27.3
Depth of main deck, D_{max} [m]	14.6
Draft, T_{full} [m]	8.5
Speed v [knots]	18
Crew [persons]	25
TEU	1100

Figure 1 presents the general arrangement of the container ship. With a red border are evidenced the amidships cargo holds analysed from the global-local strength and fatigue criteria point of view. Also that cargo hold structure has been submitted to the optimization process. According to the Germanischer Lloyd Rules [10], for the 1100 TEU container ship are considered at least the full cargo and an intermediate cases. The following mass diagrams are presented:

- Fig. 2 the full cargo load case 1, with initial structure;
- Fig. 3 the intermediate (without containers on deck) load case 2, with optimized structure.

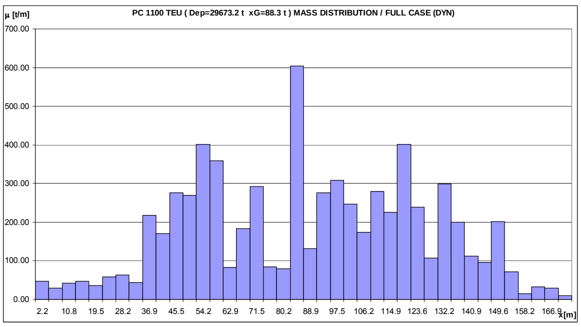

Fig. 2: Mass distribution – Full load, initial structure

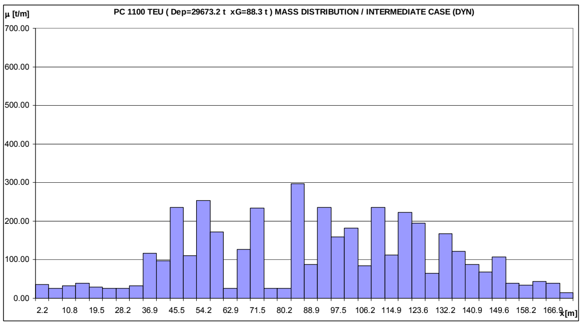

Fig. 3: Mass distribution – Intermediate load, optimized

3. GLOBAL-LOCAL ANALYSIS ON 1D-GIRDER AND 3D-FEM MODELS

3.1. Strength analysis based on 1D – equivalent girder ship hull model

Based on an iterative approach for the 1D equivalent ship girder model, taking into account the free floating and trim vertical in plane equilibrium conditions, the bending moments and the shearing forces are computed for each ship loading case, initial and optimized structure, full and intermediate cargo, for still water and external equivalent quasi-static head waves with height h_w=0–12 m (and 9.326 m), step δh_w=1 m.

The deck hatchway normal stresses based on 1D model are represented in Fig. 4 and Fig. 5, in wave sagging condition, for the initial and optimized ship structures, at full loading condition. There is presented only the sagging condition, because in the hogging condition the stress values are smaller.

Table 2 presents the maximum stress values for the four analyses cases: (FI) full load, initial structure; (FO) full load, optimized amidships structure; (NDCI) intermediate loading case, initial structure; (NDCO) intermediate loading case, optimized structure.

Table 2. The maximum deck stresses at section 0.5L

Load case Deck hatchway	1D model σ_{X_RL} [N/mm^2]	
	Hogging	Sagging
FI	100.47	221.01
FO	107.18	234.32
NDCI	103.46	160.80
NDCO	109.87	170.09

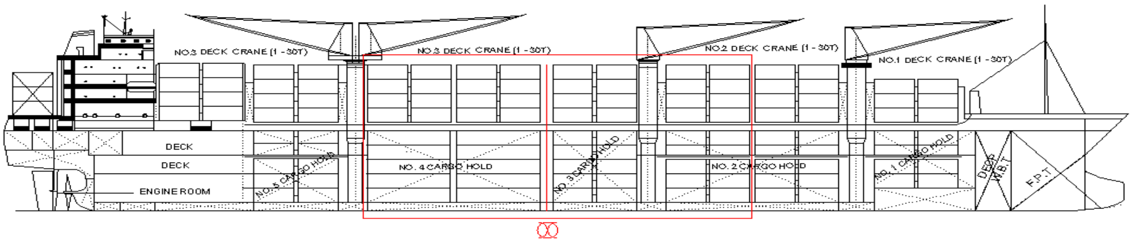

Fig. 4: General arrangement container ship 1100 TEU

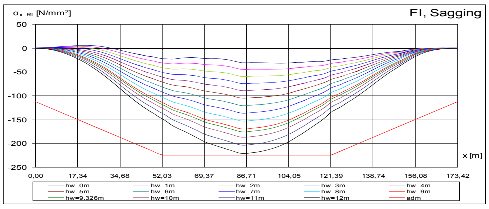

Fig. 5: Maximum deck hatchway normal stress, sagging 1D-girder model, full cargo load, initial structure

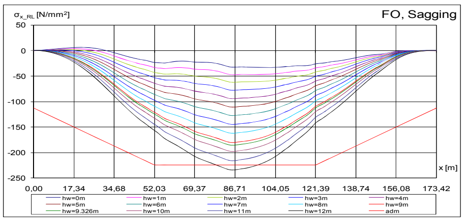

Fig. 6: Maximum deck hatchway normal stress, sagging, 1D-girder model, full cargo load, optimized structure

3.2. Strength analysis based on 3D-FEM three cargo holds model in amidships part

In order to enhance the stress state evaluation on the container ship hull structure [16],[17], the strength analysis is carried out based on a 3D-FEM model, including the three cargo holds in the amidships part (Fig.1). The boundary conditions and the loads are modelling the global-local loads for the ship hull structure. The 3D-FEM model has 207463 shell 3T elements, with 296 elements groups and 5 material properties. Fig. 7 presents the von Mises stress distribution in the container ship initial structure, full load, wave sagging condition (h_w=9.326m).

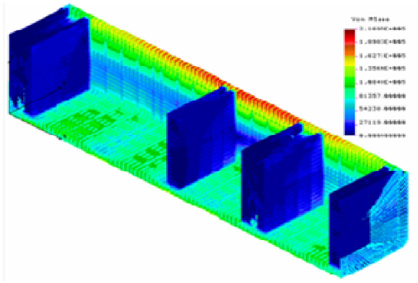

Fig. 7: Von Mises stress distribution [N/mm], full cargo load, initial structure, wave sagging h_w=9.326m

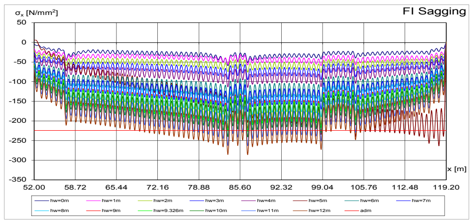

Fig. 8: Maximum deck hatchway normal stress σ_{X_RL} [N/mm^2], full cargo load, sagging, 3D-FEM, initial

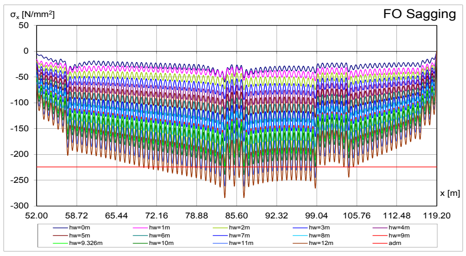

Fig. 9: Maximum deck hatchway normal stress σ_{X_RL} [N/mm^2], full cargo load, sagging, 3D-FEM, optimized

Fig. 7 points out that the maximum stresses are recorded in the deck hatchway structure. Fig 8 & 9 present the normal stress distributions at the deck hatchway, full cargo load, for the initial design and optimized structure, higher hot-spots being recorded at the intersection with the transversal bulkheads.

Table 3 presents the maximum normal and von Mises stress values at initial and optimized container ship deck hatchway, for wave height h_w = 9.326 m.

Table 3. The maximum stresses at section 0.5L, 3D-FEM

Load case	$\sigma_{vonMises\_RL}$ [N/mm^2]		σ_{X_RL} [N/mm^2]	
	σ_{vonRL_hog}	σ_{vonRL_sag}	σ_{xRL_hog}	σ_{xRL_sag}
FI	129.60	275.20	132.40	285.90
FO	129.80	274.10	132.70	284.00
NDCI	137.90	204.30	141.90	212.10
NDCO	147.40	218.00	151.60	225.60

4. THE DYNAMIC ANALYSIS BASED ON THE HIDROELASTICITY THEORY

In this section is presented the linear and non-linear 1100 TEU container ship dynamic response in irregular head waves, based on the hydroelasticity theory (coupled oscillations and vibrations).

The dynamic analyses are carried out for the head waves first order spectra ITTC [1] with the significant wave height $h_{1/3}$ = 0–12 m, step $\delta h_{1/3}$ = 0.5m, according to the Beaufort scale B_{level} = 0–11.

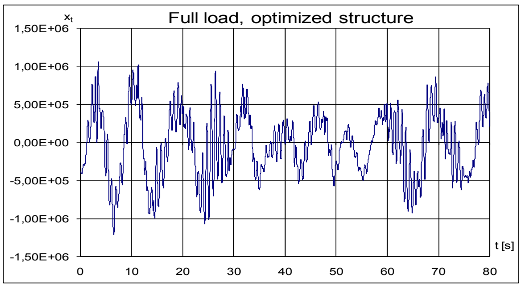

Fig. 10: Non-linear analysis, time record, irregular wave $h_{1/3}$ = 9.326 m, bending moment amidships [KNm]

The numerical results from the hydroelastic response are synthesized in the following figures:

- Fig. 8 presents the bending moment time record, from non-linear hydroelastic analysis, under irregular wave with significant height $h_{1/3}$ = 9.326 m, for the optimized structure, full cargo load, constant ship speed v =18 knots;

. Fig.9 presents the bending moment amplitude spectrum FFT, for the optimized structure, corresponding to the time record from Fig. 8.

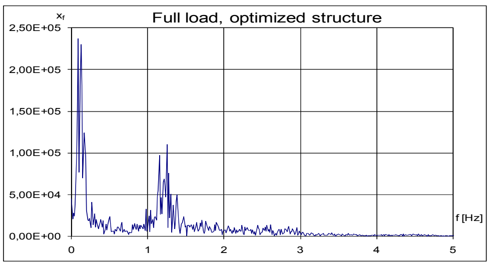

Fig. 11: Non-linear analysis, FFT amplitude spectrum, irregular wave, $h_{1/3}$ = 9.326 m, bending moment amidships

- Fig. 10 presents the maximum significant deck hatchway normal stress [N/mm^2] distribution, based on non-linear hydroelastic analysis (plus still water), $h_{1/3}$=0−12 m, v=18 knots, optimized structure, full load.

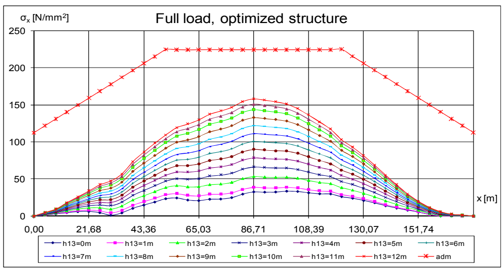

Fig. 12: Maximum deck hatchway significant normal stress [N/mm^2], non-linear analysis plus still water

5. FATIGUE DAMAGE ANALYSIS OF 1100 TEU CONTAINER SHIP

This section presents the long term fatigue damage analysis for the 1100TEU container ship and focuses on the initial service life evaluation, based on the maximum stresses for extreme wave loads obtained in the deck hatchway and in the deck shell (sections 4) and the local 3D/1D hot-spots factors (section 3) with equation (3).

The ship fatigue strength criterion is evaluated based on the cumulative damage ratio D Palmgren-Miner method and steel standard design S-N, taking into account the oscillations (low frequency) with the following expression:

$$D = D_{osc} + D_{vib}\ ;\ n_{i\_osc,vib} = p_i \cdot n_{\max\_osc,vib} \qquad (1)$$

$$D_{osc,vib} = \sum_{i=1}^{m} \frac{n_{i\_osc,vib}}{N_{i\_osc,vib}}\ ;\quad N_{i\_osc,vib} = f_{SN}\left(\Delta\sigma_{i\_osc,vib}\right)$$

$$n_{\max\_osc,vib} = 3.1536\,10^7 R \cdot f_{osc,vib};\ \ \Delta\sigma_{i\_osc,vib} = 2\sigma_{1/3i\_osc,vib} \cdot f_c$$

where: $f_{osc,vib}$ are the natural ship frequencies for oscillation and vibration modes; $n_{max\_osc,vib}$ are the maximum number of cycles; $p_i(h_{1/3i})$, $i=1,m$ are the probabilities of World Wide Trade (WWT) wave significant height $h_{1/3}$ histogram (Fig. 12); $n_{i\_osc,vib}$ are the number of stress cycles for $h_{1/3i}$; $N_{i\ osc,vib}$ are the number of endured stress cycles from the steel standard design S-N curves for a stress range $\Delta\sigma_{i\_osc,vib}$.

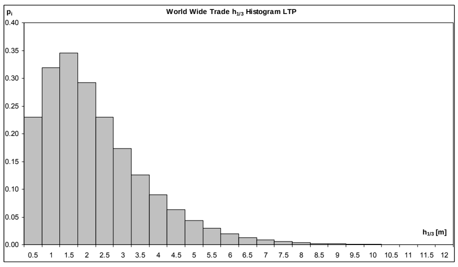

Fig.13: World Wide Trade wave height $h_{1/3}$ histogram

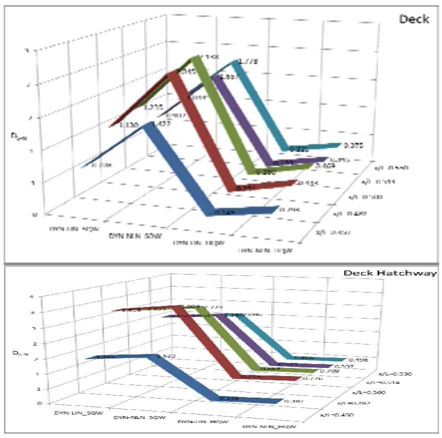

Fig. 14: The fatigue damage ratio D, ship rigid body hypothesis (oscillations), for long term World Wide Trade significant wave height histogram, at deck hatchway and main deck, initial structure, v=18knots

The estimated service life of the container ship hull from the fatigue strength criterion, with reference time of R = 25 years, using equation (1) results from the following expressions:

$$L = 25/D\,;\ D_{FI\&NDCI} = 50\%\cdot D_{FI} + 50\%\cdot D_{NDCI} \quad (2)$$
$$D_{FO\&NDCO} = 50\%\cdot D_{FO} + 50\%\cdot D_{NDCO}$$

In order to obtain a realistic fatigue analysis, based on the 1D and 3D-FEM models (section 3), there is computed the stress 3D/1D correlation coefficient $k_{3D/1D}$, based on the following expression:

$$k_{3D/1D} = \max\left\{\frac{\sigma_{VM\_3D\_sag}}{\sigma_{x\_1D\_sag}}, \frac{\sigma_{VM\_3D\_hog}}{\sigma_{x\_1D\_hog}}\right\} \quad (3)$$

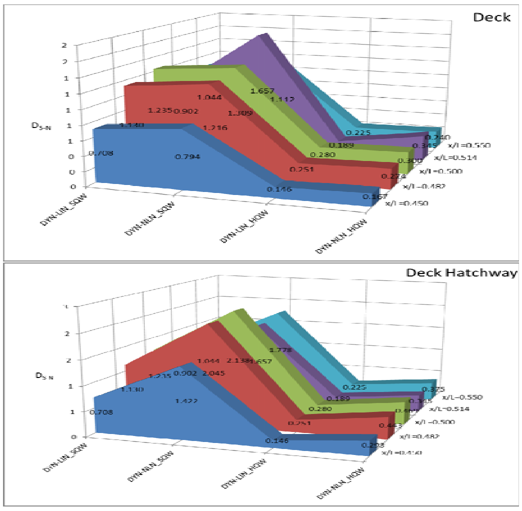

Fig. 15: The fatigue damage ratio D, elastic ship girder hypothesis (hydroelastic, oscillations and vibrations), for long term World Wide Trade significant wave height histogram, at deck hatchway and main deck, initial design structure, v=18knots

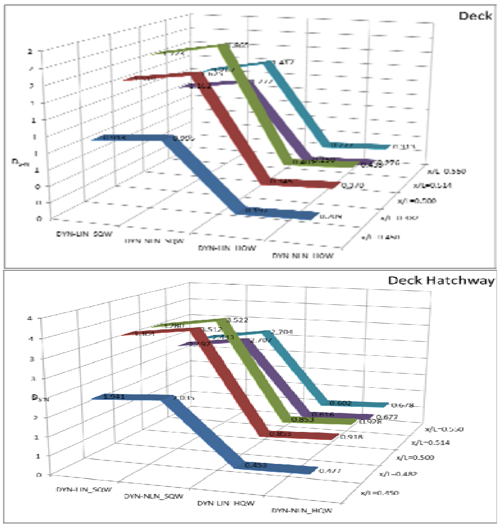

Fig. 16: The fatigue damage ratio D, ship rigid body hypothesis (oscillations), for long term World Wide Trade significant wave height histogram, at deck hatchway and main deck, optimized, v=18knots

The influence of the butt weld joints welding quality, [9], [10], standard or very good welding, is also taken into account in equations (1) and (2).

Figs. 13-16 present the diagrams for the fatigue cumulative damage factor D, computed under the ship rigid body (oscillations) and ship elastic girder (hydroelasticity, oscillations & vibrations) hypothesis, for long term World Wide Trade wave significant histogram, ship speed 18 knots, for initial design and optimized structure, at deck hatchway and deck shell for five sections with relevant hot spots (0,45 – 0.55 L).

Table 4 presents the cumulative damage factor D and the estimated ship service life L [years].

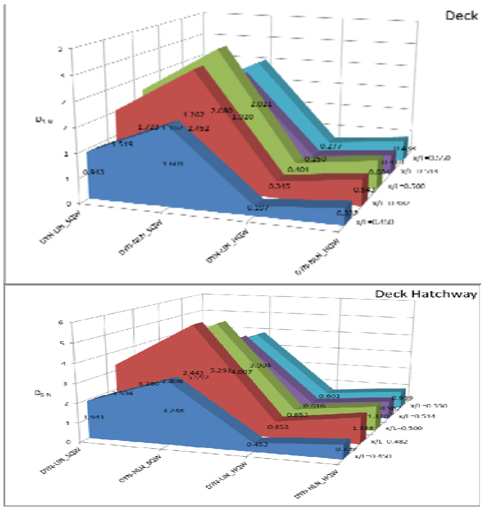

Fig. 17: The fatigue damage ratio D, elastic ship girder hypothesis (hydroelastic, oscillations and vibrations), for long term World Wide Trade significant wave height histogram, at deck hatchway and main deck, optimized structure, v=18knots

Table 4. Fatigue analysis results for initial design and optimized structures, combined full & intermediate cases

Deck shell	weld	D	L [years]	D	L[years]
Oscillations		Initial design		Optimized	
DYN-LIN	std.	1.235	16.2	1.723	11.6
DYN-NLN	std.	1.309	15.3	1.865	10.7
DYN-NLN	hq.	0.300	>25	0.435	>25
Hydroelastic		Initial design		Optimized	
DYN-LIN	std.	1.235	16.2	1.723	11.6
DYN-NLN	std.	2.138	9.4	2.680	7.5
DYN-NLN	hq.	0.469	>25	0.604	>25
Deck hatchway	weld	D	L [years]	D	L[years]
Oscillations		Initial design		Optimized	
DYN-LIN	std.	2.622	7.6	3.280	6.1
DYN-NLN	std.	2.773	7.2	3.522	5.7
DYN-NLN	hq.	0.709	>25	0.928	>25
Hydroelastic		Initial design		Optimized	
DYN-LIN	std.	2.622	7.6	3.280	6.1
DYN-NLN	std.	4.829	4.1	5.293	3.8
DYN-NLN	hq.	1.161	17.2	1.320	15.2

6. CONCLUSIONS

The numerical results from sections 3 and 4 are pointing out that the maximum stresses are recorded in the deck shell and deck hatchway around section 0.5 L, so that the interest domains are 0,45-055 L.

The fatigue analyses based only on oscillations response (standard approach) estimates on long term the following cumulative damage ratios:

- D_{SN} = 0.429 – 2.773 presented in Table 4 and graphically in Fig.13, leads to a minimum of 7.2 years ship service life, for the initial designed structure and standard welding case;
- D_{SN} = 0.435– 3.522 presented in Table 4 and graphically in Fig.15, leads to a minimum of 5.7 years ship service life, for the optimized structure and standard welding case.

The fatigue analyses based on oscillations and vibrations response (advanced hydroelastic approach) estimates on long term the following cumulative damage ratios:

- D_{SN} = 0.300 – 4.829 presented in Table 4 and graphically in Fig.14, leads to a minimum of 4.1 years ship service life, for the initial designed structure and standard welding case;
- D_{SN} = 0.604– 5.293 presented in Table 4 and graphically in Fig.16, leads to a minimum of 3.8 years ship service life, for the optimized structure and standard welding case.

In the case of very good welding the service life becomes larger than 25 years in standard approach and lower in advanced approach, the optimized structure having 15.2 years instead of 17.2 years as for the initial design structure. The optimized structure is more sensitive on the fatigue assessment, having higher stresses but les weight as the initial one.

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