Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 22 (2019) 110–117

Structural Integrity Procedia

www.elsevier.com/locate/procedia

First International Symposium on Risk and Safety of Complex Structures and Components

Structural resistance of lightweight stiffened panels submitted to buckling

João G. Guerreiro[a], Rui F. Martins[b,*], Ricardo Filipe P. Batista[c]

[a] *Faculty of Sciences and Technology, Universidade NOVA de Lisboa, Department of Mechanical and Industrial Engineering, Campus de Caparica, 2829-516 Monte de Caparica, Portugal*
[b] *UNIDEMI, Faculty of Sciences and Technology, Universidade NOVA de Lisboa, Department of Mechanical and Industrial Engineering, Campus de Caparica, 2829-516 Monte de Caparica, Portugal*
[c] *Direção de Navios, Base Naval de Lisboa, Alfeite, 2810-001 Almada, Portugal*

Abstract

The primary goal of the study herein presented was to evaluate the remaining strength of a stiffened panel belonging to a ship's deck that suffered some deformations during service.

For this purpose, some representative panels of the ship were modelled, aiming to simulate a range of typical deformations, from the ones found on board, as is, through to some extreme cases of deformations that could lead to structural collapse. After shaping the stiffened panels, compressive in-plane loading was applied, simulating longitudinal bending of the hull in a sagging condition. Non-linear structural analyses were carried out using the Finite Element Method (FEM) and ANSYS software.

It was found that the existence of large deformations between reinforcements led to the loss of strength of the original stiffened panel and the local deformations occurring near the reinforcements do not affect the strength of the panel significantly. The case with a higher loss of strength was the one relative to the collapse of a longitudinal reinforcement profile of the deck panel. In addition, the main types of buckling found in the panel were the local buckling of plating between stiffeners and the lateral-torsional buckling of the smaller stiffeners.

Despite the moderate loss of strength found on some of the stiffened panel studied, it was possible to conclude that this loss of strength does not compromise the normal safe operation of the ship, even in extreme load.

Keywords: Lightweight stiffened panels; Remaining strength; Collapse modes; Finite element analysis; Nonlinear analyses.

---

* Corresponding author. Tel.: +351-212-948-567; fax: +351-212-948-531.
E-mail address: rfspm@fct.unl.pt

10.1016/j.prostr.2020.01.015

1. Introduction

Ships are generally subjected to loadings induced by the operating conditions, which, in some cases, can lead to large deformations, structural instability, or even failure (Martins *et al.* (2009), Martins *et al.* (2013) and Bugio *et al.* (2013)). Those loadings are frequently causing crack initiation and propagation under Mode-I, II and/or Mode-III loading (Martins *et al.*, 2016), and the determination of the fatigue crack growth rates curves, under specific environmental conditions (Martins and Branco, 2004), are relevant to predict the fatigue life of a structure or component in case of a damage tolerance approach applies.

The vessel under study is classified as a large landing craft (LLC), which was designed for cargo transportation and landing ability for loading and unloading (Fig. 1). This type of operation typically involves handling and stowing of heavy cargo of the most diverse nature (general cargo, heavy vehicles, personnel, etc.) and is liable to cause damage. These damages, usually caused by overloads, impact, or accidents, cause changes in the structure of the ship and may affect the stability of reinforced structural panels locally.

Fig. 1. Large landing craft (LLC) under study.

2. Ultimate limit state

Marine structures are subject to various types of loads and deformations resulting from in-service requirements, which may vary from regular to the extreme of an accidental situation. A limit state is conventionally defined by the condition in which a specific structural member, or even the entire structure, fails to fulfil the function for which it was designed. From a structural designer point of view, four types of limit states are considered for steel structures, Paik and Thayamballi (2013), namely:

- SLS – serviceability limit state
- ULS – ultimate limit state
- FLS – fatigue limit state
- ALS – accidental limit state

The ultimate limit state, also referred to as maximum strength state (Fig.2), typically represents the collapse of a structure due to loss of stiffness and/or strength. This disability may be related to loss of equilibrium of part or all structure, or the ultimate strength of a region by rupture or fracture, or even the instability of part or all structure due to buckling and plastic collapse of a reinforced panel.

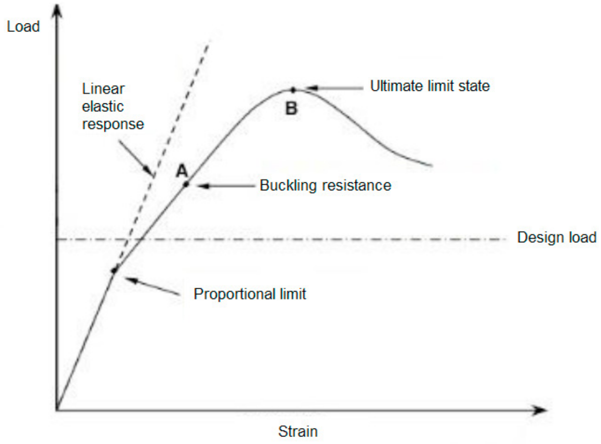

Fig. 2. Design considerations based on the ultimate limit state.

In practice, the ultimate limit state concept implies that the designer considers the post-buckling behaviour of the various components (Fig. 2, beyond Point A) and the interaction between them. Moreover, to obtain a safe and economic structure, the design loads must be evaluated correctly, and the designer must even calculate the maximum strength not only for the as-fabricated structure but also for structures with some damage, so that the safety factor of the damaged structure can be assessed. By doing this, the safety margin of a structure can be evaluated by comparing its maximum resistance with the maximum loads that can be applied (design load) (Fig. 2).

The paper herein presented aims to compare the compressive strength of a representative panel belonging to a deck of a ship, as designed, with its remaining resistance after it has undergone some deformation during service.

2.1. The collapse of primary, secondary and tertiary structures of a ship

A typical structural arrangement of a maritime structure and its structural response is generally described at three significant levels, namely primary, secondary and tertiary levels. The primary level refers to the entire structure, as a whole, and takes into account its overall behaviour. Hence, the primary structural response is the response of the entire hull when subjected to bending and twisting, as a single beam, under the actions of the primary external loads. The secondary structure refers to the elements that provide the local structural strength, namely the reinforced panels constituted by the longitudinal and transversal reinforcements and the plates (Fig.3). The panel loading is usually perpendicular and/or coplanar to the plane of the plates. Finally, the tertiary level is represented by the simpler structural elements, i.e. the plates between the structural reinforcements. It describes the lateral and axial deformation of the unreinforced sheet panel which is welded to reinforcing profiles on both sides. The loading usually is perpendicular and/or coplanar to the plane of the plates.

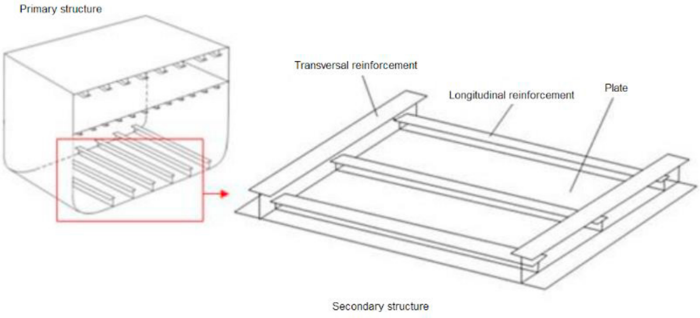

Fig. 3. Detail of a reinforced panel (secondary structure).

Besides, with increasing compressive loads applied on a reinforced panel, a global or local buckling collapse may occur if the load reaches a critical value. Hence, when the structural reinforcements are too slender, the reinforced panel could fully bend in a manner known as a global buckle; on the other hand, when the reinforcements are significantly more resistant, they remain intact until the plates between them locally bend. Inversely, if the reinforcement web is too high or too thin, it bends as if it were sheet metal. Additionally, when the torsional stiffness of the reinforcement is not sufficiently high, it twists in a manner which is referred to as flexo-torsional buckling. Nevertheless, although each form of buckling was described separately, they can interact and can co-occur during the collapse of a reinforced panel.

3. Case study

3.1. Determining the maximum bending moment and the extreme stresses induced in the panel under study

The reinforced panel under study (Fig.4) is located amidships, between transversal and longitudinal bulkheads (red lines in Fig.4), in a zone subjected to a maximum longitudinal bending moment, and belongs to a ship that entered in service in 1985 with the following main characteristics:

- Total length, L: 56.54 m
- Maximum width of the ship (beam): 11.80 m
- Moulded depth: 3.05 m
- Moulded draft: 1.35 m
- Displacement: 653 ton
- Power: 1600 cv

The panel presented in figure 4 is half-modelled along the longitudinal direction; hence, a symmetry condition was defined during the finite element analyses carried out.

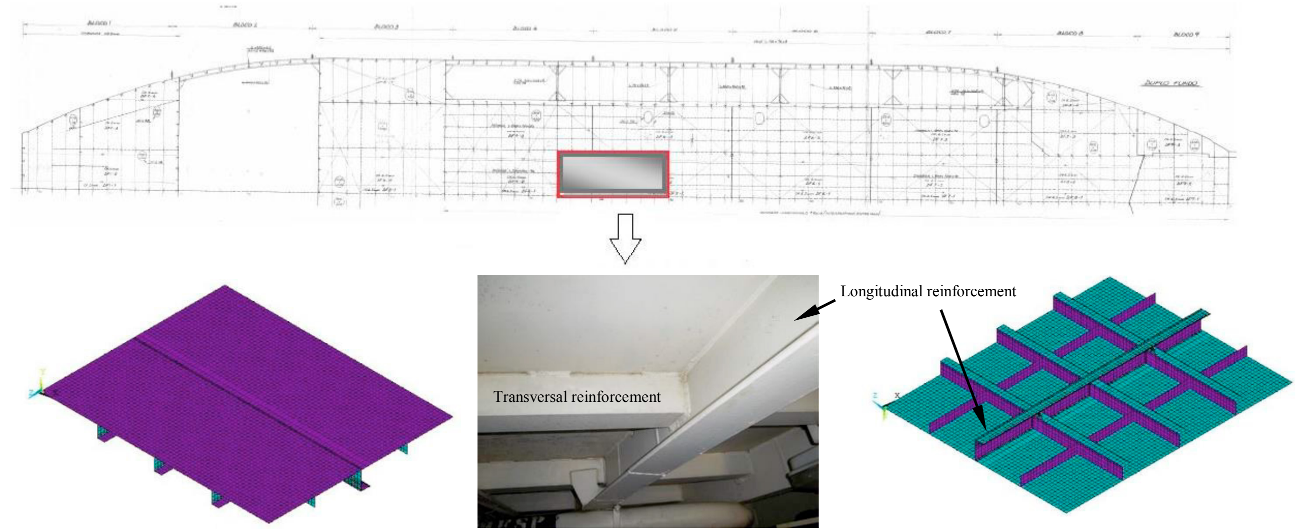

Fig. 4. Overall view of the reinforced panel modelled (2000x2500 mm).

In order to assess the maximum theoretical bending loading induced in the ship due to sagging (Fig. 5a), a trochoid wave of the same length as the vessel was considered (56.54 m). The ship was divided into twenty sections of equal length (Fig. 5b), and the weight and buoyancy were determined, in every section, as well as the distributed loading curve (transverse load). For buoyancy, the immersed volume was calculated according to the height of the wave considered, H, which was equal to 4.564 m ($H = 0.607(L)^{0.5}$, Tupper (2004)), and the weight corresponded to a maximum equivalent load of 900 ton, which was distributed along the length of the ship, having into account the superstructure's arrangement and the available ship's width (Fig. 4). Therefore, shear force, V(x), and bending moment distribution, M(x), were determined from the resultant load curve and by integrating V(x), respectively (Fig. 6a, 6b).

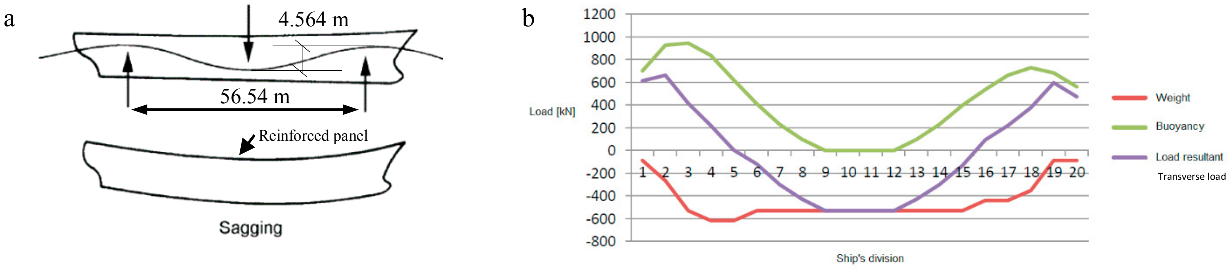

Fig. 5. (a) Sagging condition; (b) Weight, buoyancy and resultant load considered in the sections of the ship.

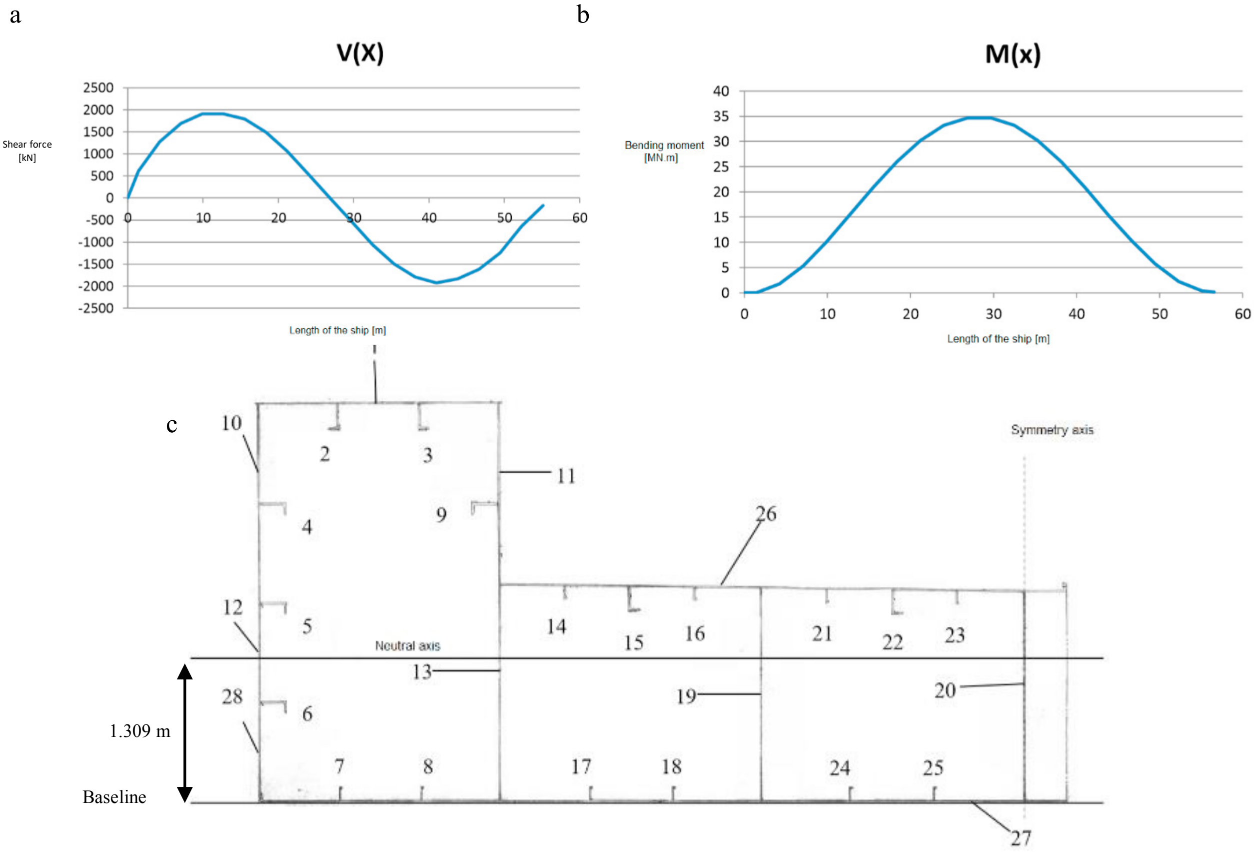

Fig. 6. (a) Transverse load distribution, V(x); (b) Bending moment distribution, M(x); (c) Half-view of the midship cross-section with structural profiles numbered.

A maximum bending moment of 35 MN.m was estimated to be applied amidships of the vessel (Fig. 6a), and the neutral axis location was determined 1.309 metres above the baseline of the ship, as shown in Fig. 6c. Additionally, the moment of inertia of the section of each structural profile allowed to calculate a moment of inertia of the master's midship cross-section equal to 0.49 m^4, resulting in an extreme induced stress of 25.5 MPa at the reinforced panel under study.

3.2. Introduction of damage in the reinforced panel under study

As the objective of this work was to compare the maximum strength of the as-designed panel with the same panel subjected to some typical deformations, these were introduced in the model (Fig.7a) (Guerreiro, 2012). The depth of the concavities simulated in the numerical analyses ranged from 5% to 15% of the distance between the transverse reinforcements of the panel; moreover, the concavities were assumed to be located either at midspan between reinforcements (Fig.7a), or close to the longitudinal reinforcements (Fig.7b), or closer to the transverse reinforcements (Fig. 7c). Besides the cases referred, the simulation of a reinforced panel without one longitudinal profile was also considered (Fig.7d), as well as a panel with a spot defect.

3.3. Boundary conditions, external loads, material models and Finite Element (FE) solution controls

The boundary conditions specified in the numerical analyses carried out are indicated in Fig. 7a and assumed the existence of symmetry along the longitudinal direction of the panel (x-axis), as well as the presence of longitudinal and transverse bulkheads placed at the other contours. Moreover, the loading of the panel – due to sagging condition – was simulated through the application of increasing displacement values, UX≠0, to the transverse edge shown, and the existence of cargo in the ship's deck was considered by the application of a lateral load pressure equal to 30kN/m^2.

Additionally, the numerical analyses were carried out using ANSYS software and considered large displacement, prestress effects and an automatic time stepping. Two-dimensional eight-node shell element, SHELL281, were used for the FE mesh and the elastic behaviour of the material was defined through a Young's Modulus, E, equal to 205 GPa and a Coefficient of Poisson of 0.3. A bilinear isotropic material model was also used to simulate hardening; therefore, a Yield Stress equal to 315 MPa was considered, as well as a Tangent Modulus, E_T, of 40 GPa. The elastic perfectly plastic material model considered a Tangent Modulus equal to approximately 1 GPa.

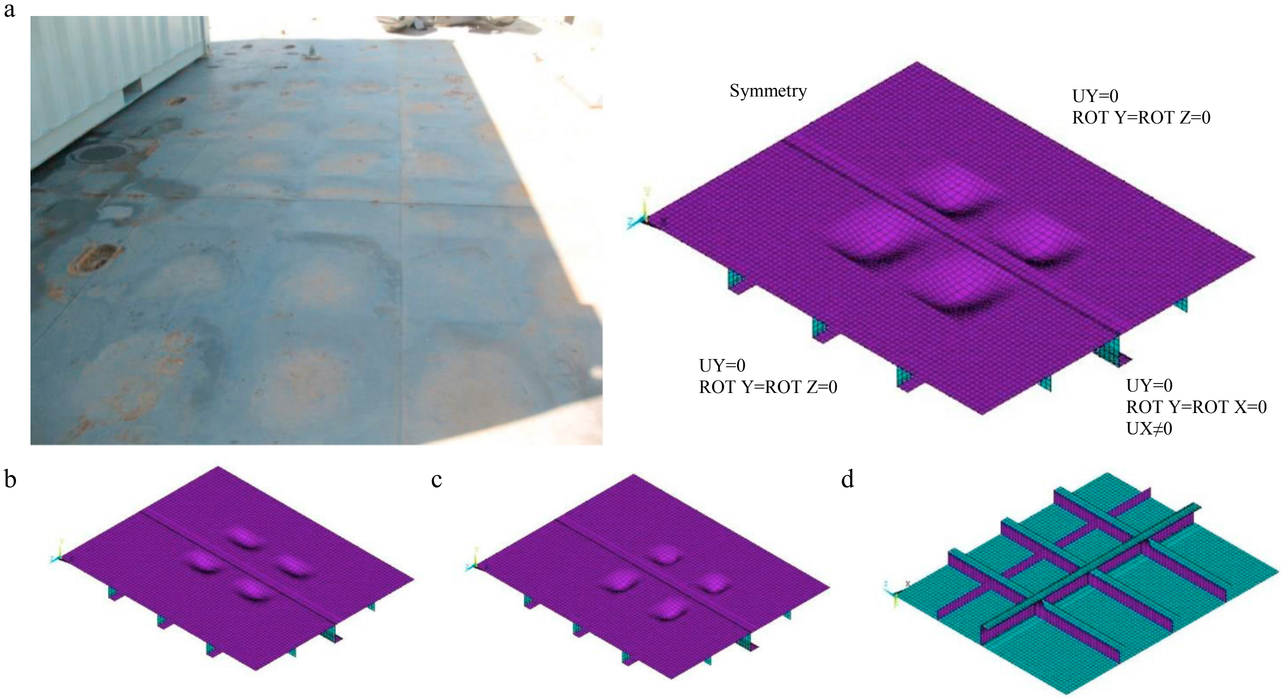

Fig. 7. (a) Panel with concavities uniformly distributed between the reinforcements; (b) Panel with concavities introduced closer to the longitudinal reinforcements; (c) Panel with concavities introduced closer to the transverse reinforcements; (d) Reinforced panel without one longitudinal profile.

4. Results

4.1. Reinforced panel (as-designed)

The as-designed reinforced panel, made of an elastoplastic ($E_T/E=0$) and a strain-hardening type material ($E_T/E=0.2$), was numerically analysed to determine its mechanical behaviour and the maximum resistance that characterises it (Fig. 8a). Accordingly, the maximum stress value that can be applied to the panel was 218.4 MPa, which was calculated by dividing the reaction forces by the transverse cross-section area of the stiffened panel. This value, lower than the yield stress of the material, is the load that causes structural instability and, locally, the yielding of some areas of the panel. Nevertheless, a safety factor of 8.5 can be calculated having into account the static design load (25.5 MPa) and the stress value determined numerically (Fig. 8a). Moreover, the longitudinal reinforcements present, as expected, the highest induced stresses, these being the structural elements that resist the requests in the longitudinal direction (Fig. 8b); inversely, transverse stiffeners do not exhibit significant stresses. Additionally, there are weld beads between the primary reinforcements and the plates where yielding was noticed, and the stress distribution in the plate is irregular, alternating zones with high stress and others with negligible stress. The largest displacements occur in the plates between reinforcements (Fig. 8c), and the slender longitudinal stiffeners are the first to accuse the compression effort by showing some twisting of their webs (Fig. 8b).

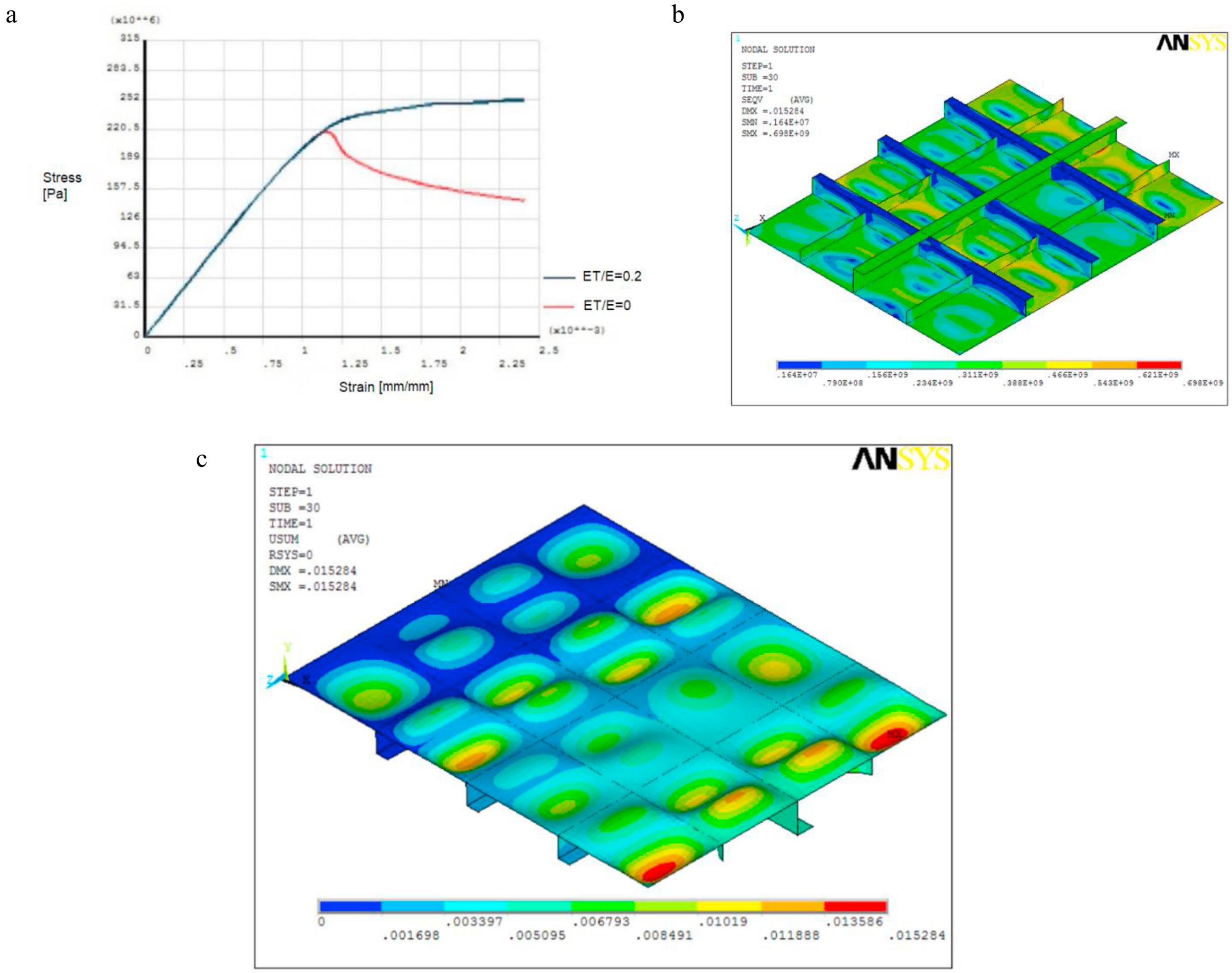

Fig. 8. Reinforced panel (as-designed) (a) Stress-strain relation considering an elastoplastic and a strain hardening material; (b) Stress distribution registered in the reinforced panel; (c) Displacements [m].

4.2. Reinforced panel with uniform concavities

The same analysis was carried out on panels with uniform concavities between reinforcements (Fig. 7a). The analyses allowed to determine the stress-strain curves of the panel at three different deformation depths: 5%, 10% and 15% of the distance between transverse reinforcements, in order to understand how the depth of the deformation can influence the strength of the reinforced panel. In Fig. 9 the results of these three different cases were superimposed with the as-designed panel for comparison. From the observation of the determined stress-strain curves, the decrease of the maximum resistance of the panel is verified as the depth of the deformation increases. In fact, a greater difference in structural strength is observed between the as-designed panel and the panel with the concavities of 5% (8.4% decrease); the percentage of variation of the structural strength decreases as the deformation depth increases (5% and 2.3%), being at most equal to 15% (comparing the maximum resistance of the perfect panel vs the panel with uniform concavities of 15%).

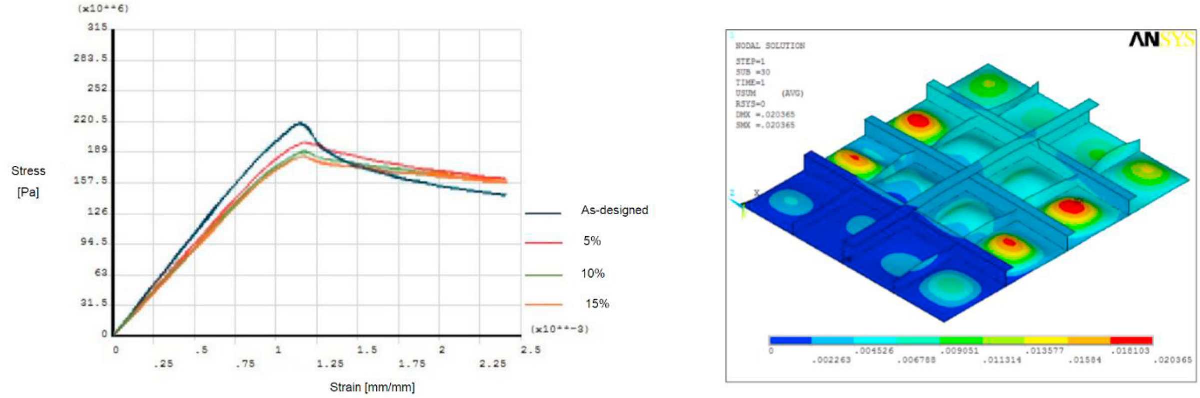

Fig. 9. Reinforced panel with uniform concavities: stress-strain relation considering an elastoplastic material.

5. Conclusions

Despite the loss of resistance of the panel found in the most critical cases of this study, the deformations modeled do not, per se, compromise the normal operation of the ship. In fact, the design load (25.5 MPa) remained well below the maximum allowable stress which was, at worst, 186 MPa (Fig.8).

Acknowledgements

The authors would like to thank the Portuguese Foundation for Science and Technology through project ref. UID/EMS/00667/2019.

References

Bugio, Tiago M. A., Martins, Rui F., Neves, L. Leal das, 2013. Failure analysis of fuel tanks of a lightweight ship, Engineering Failure Analysis 35, 272-285.

Guerreiro, J.F.G., 2012. Study of the remnant structural strength of reinforced panels subjected to buckling, Master of Science Thesis (in Portuguese), Faculty of Sciences and Technology, Universidade NOVA de Lisboa.

Martins, Rui F., Ferreira, L., Reis, Luís, Chambel, P., 2016. Fatigue crack growth under cyclic torsional loading, Theoretical and Applied Fracture Mechanics 85, 56–66.

Martins, R., Branco, C.M., 2004. A fatigue and creep study in austenitic stainless steel 316L used in exhaust pipes of naval gas turbines, Fatigue Fract Engng Mater Struct 27, 861-871.

Martins, R.F., Moura Branco, C., Gonçalves-Coelho, A.M., Gomes, Edgar C., 2009. A failure analysis of exhaust systems for naval gas turbines. Part II: Design changes, Engineering Failure Analysis 16, 1324-1338.

Martins, Rui F., Rodrigues, Hugo, Neves, L. Leal das, Silva, Pires da Silva, P., 2013. Failure analysis of bilge keels and its design improvement, Engineering Failure Analysis 27, 232–249.

Paik, J. K., Thayamballi, A. K., 2003. Ultimate Limit State Design of Steel-Plated Structures, In: John Wiley and Sons (Ed.), ISBN 9780471486329

Tupper, E., 2004. Introduction to Naval Architecture. In: Elsevier Butterworth-Heinemann (Ed.), Oxford, 283.