FEM analysis of ultimate strength of steel panels

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ABSTRACT

A method was described of ultimate strength calculation of compressed steel panels proposed for shipbuilding applications. The calculations consist in applying Finite Element Method (FEM) to a model composed of finite shell elements. Large displacement values and plastic flow of material are taken into consideration. Results of ultimate strength calculations of an example panel under compression were compared with those from experimental tests. Accuracy of a proposed simple method of ultimate strength assessment based on the longitudinal bending theory of rod with initial deflections, was also investigated.

Keywords : laser-welded steel panels, ultimate strength of steel structures, finite element method calculations in the non-linear range

INTRODUCTION

A research project concerning engineering processes and strength of steel panels was conducted at Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology, [2]. Within the frame of the project manufacturing process of steel panels with the use of laser welding technique was elaborated, as well as some structural strength tests of the axially compressed panels under lateral load were performed. Results of the tests are presented in [3] and [4].

Construction of a typical panel is shown in Fig.1. It consists of flat steel plates of t = 3.0 mm thickness, mutually connected by means of steel webs of t = 4.0 mm thickness, 60 mm depth, and 80 mm spacing. The plates are laser-welded to the webs. Such welding technique ensures weld penetration through not full thickness of webs (Fig.1). The so obtained joint constitutes a significant notch in panel's structure and determines the immediate and fatigue strength of such structures.

a) Cross-section

b) Joint between plating and web

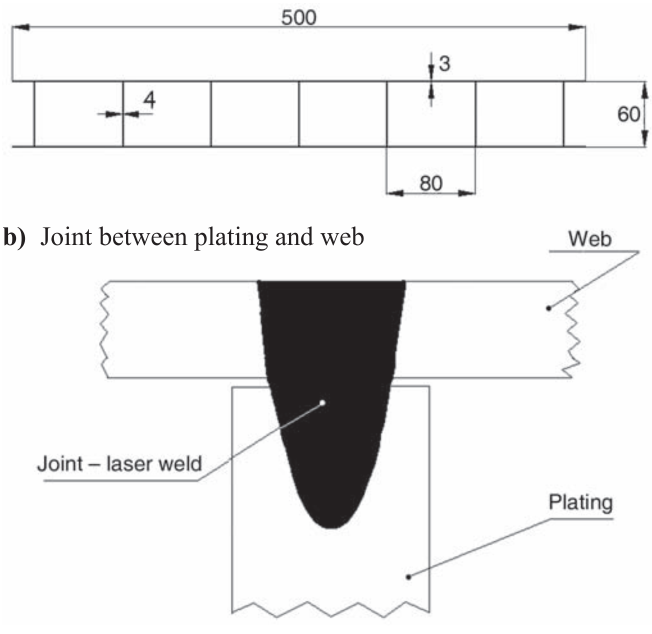

Fig. 1. Construction of the panel .

In this paper are presented results of FEM strength calculations of the axially-compressed panel of l = 3.0 m in length, shown in Fig.1a. The calculations were aimed at checking if the FEM non-linear calculations where shell model of the panel has been applied, provide values of ultimate loads of the panels under axial compression, close to those experimental, described in [3] and [4]. Possible application of the simple theory of eccentrically compressed rod, proposed in [1], to ultimate strength assessment of compressed panels, is also discussed.

ELASTIC BUCKLING OF THE COMPRESSED PANEL

Strength of the panel under axial compression was assessed by using the model of compressed rod of the cross-section as in Fig.1, l = 3.0 m in length, and hinge-supported ends.

In this case the theoretical critical stresses σ_E are as follows :

$$\sigma_E = \frac{\pi^2 E I}{l^2 A} \tag{1}$$

where :

$E = 2.06 \cdot 10^5$ N/mm^2 - Young modulus of steel
$I = 3.483 \cdot 10^{-6}$ m^4 - inertia moment of the cross-section shown in Fig.1a
$l = 3.0$ m - length of the rod
$A = 4.68 \cdot 10^{-3}$ m^2 - cross-sectional area of the rod shown in Fig.1a.

From the calculations by using (1) the following was obtained : $\sigma_E = 168$ MPa.

The value of the theoretical critical force $P_E = \sigma_E A = 0.786$ MN.

The elastic buckling of the panel under axial load was investigated also by using FEM calculations with application of NEi/Nastran computer software [5]. The applied FEM model is shown in Fig.2.

The model was built of the quadrilateral four-node finite shell elements of CQUADR type placed in the mid-thickness of panel plating. In such model the details of the plate-web joints shown in Fig.1b, are not taken into account. The linear elastic stress-strain model of the material having Young's modulus $E = 2.06 \cdot 10^5$ MPa and Poisson's ratio $\nu = 0.3$, was assumed.

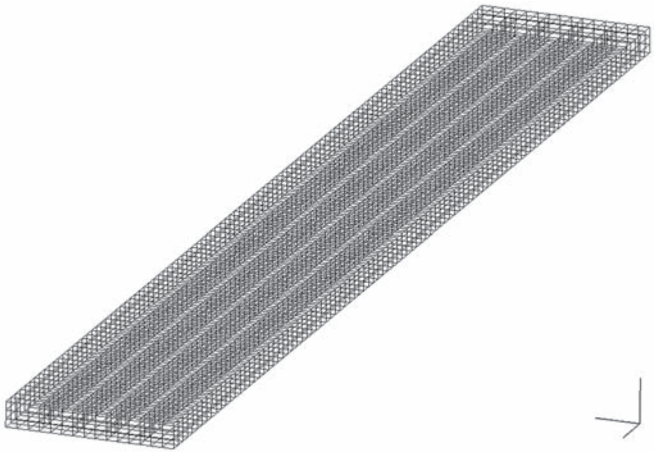

Fig. 2. *The FEM model of the panel, used for elastic buckling calculations .*

The calculated value of the theoretical critical force (total compression force applied to the panel) relevant to the basic form of elastic buckling shown in Fig.3, amounts to $P'_E = 0.800$ MN. The force P'_E is greater only by 1.8% than P_E. It is consistent with expectations that $P'_E > P_E$. As a rule FEM model yields an excessively large value of structural stiffness.

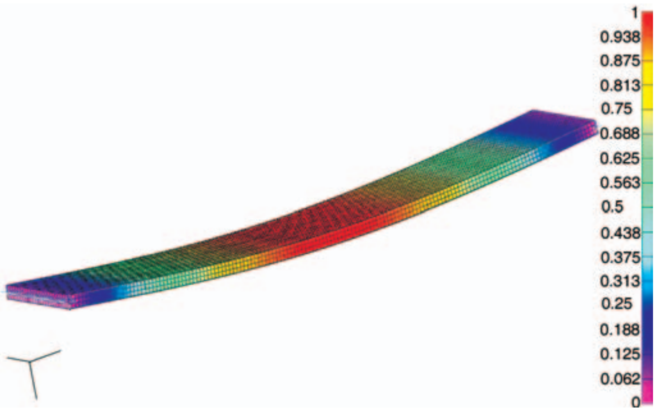

Fig. 3. *The basic form of elastic buckling .*

ULTIMATE STRENGTH CALCULATIONS OF COMPRESSED PANEL

In the FEM calculations, plastic flow of material and influence of deformations (panel deflections) on values of internal forces and stresses were taken into account. The material plastic flow was assumed in compliance with the model based on associate principle of plastic flow. The assumed simplified $\sigma - \varepsilon$ characteristics of material under uniaxial tension/compression is shown in Fig.4.

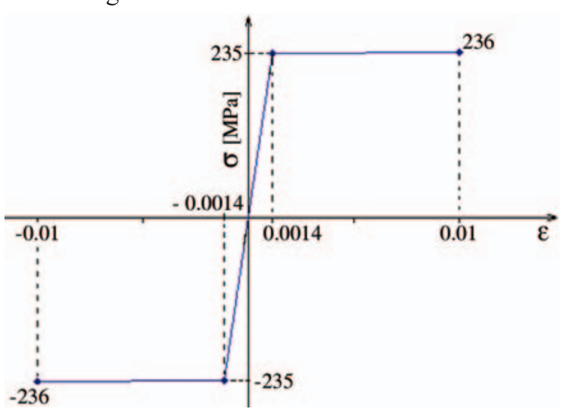

Fig. 4. *The assumed $\sigma - \varepsilon$ characteristics of material .*

It was assumed that the panel is freely-supported at the ends, and some longitudinal displacements of one of the ends were uniformly exerted to all webs (the support and forced displacements were applied to the points at the mid-depth of the webs). The FEM model of the panel, built of quadrilateral finite shell elements of CQUADR type (acc. [5]) is presented in Fig.5. The model does not take precisely into account the features of the welded joint connecting web and plating, shown in Fig.1b.

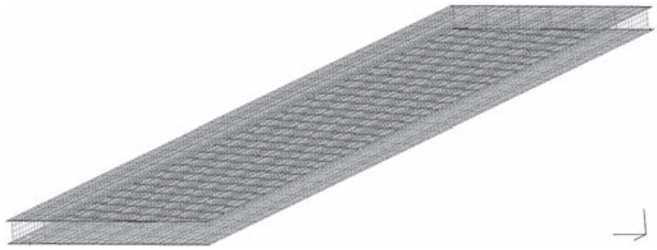

Fig. 5. *FEM model of the panel .*

The calculations were performed for the panel with an imperfection assumed in the form of an initial cylindrical deflection in the plane of the webs. The shape of the initial deflection was approximated with the use of third-order spline (of zero-value of second derivatives at ends), symmetrically with respect to the plane perpendicular to the webs, at their mid-length. The calculations were performed for a few values of the initial deflection δ, namely: 2.5 mm, 5.0 mm, 7.5 mm and 10 mm.

The NEi/Nastran software was used again. The calculations consisted in determining the state of equilibrium of the panel, corresponding with successive, systematically increasing values (steps) of the longitudinal displacement of one of the panel's ends, Δl. The assumed step of set displacements was equal to 0.5 mm.

The typical damage mode of the structure is shown in Fig.6 (initial deflection of 2.5 mm ; $\Delta l_{max} = 12.5$ mm)

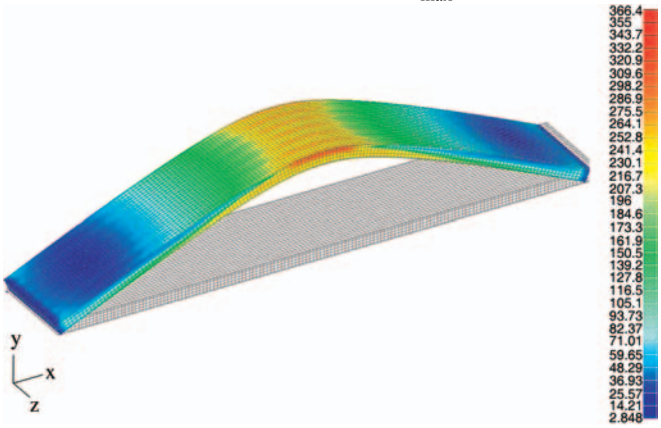

Fig. 6. *Mode of the panel's damage .*

In the diagrams in Fig.7 is shown the value of the compressive force P applied to the panel in function of the decrease of distance between its ends, obtained from solving the above described non-linear FEM model.

The maximum values P_{max} of P forces in the diagrams (Fig.7) are considered as the critical forces (ultimate strength) of the axially compressed panels. They are presented in Table.

In Table are also presented values of the critical forces estimated with the use of the theory described in [1]. The theory concerns the axially compressed rod with initial deflection of the maximum value δ at its mid-length.

As defined by this theory, the ultimate strength of the rod is deemed exhausted when the extreme value of summary stresses

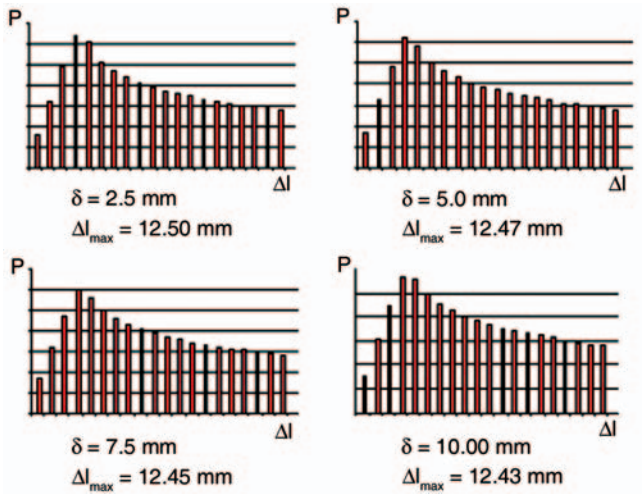

Fig. 7. *The value of the compressive force P applied to the panel versus the decrease of distance between its ends .*

in extreme fibres of the rod, resulting form axial compression and bending due to initial deflection of the rod, exceeds the level of yield strength of material. If to assume that the compressive force is applied just to the rod's axis and the rod is freely-supported at its both ends then the above mentioned condition can be described by the following equation :

$$\sigma_Y = \frac{P_u}{A} + \frac{P_u\,\delta}{\left(1 - \frac{P_u}{P_E}\right) Z} \qquad (2)$$

where :

σ_Y - yield strength
P_u - extreme value of compressive force
A - cross-sectional area of the rod
δ - maximum value of initial deflection
Z - strength modulus of cross-section of the rod
$P_E = \frac{\pi^2 EI}{l^2}$ - theoretical value of the critical force
E - Young modulus
I - inertia moment of cross-section of the rod
l - length of the rod.

In the equation (2) were applied : the parameters A, Z, I of the cross-section shown in Fig.1a, the panel's length l = 3.0 m, as well as the properties of normal steel ($E = 2.06 \cdot 10^5$ MPa, $\sigma_Y = 235$ MPa). On this basis P_u values were determined for a few values of δ, as presented in Table.

Table. *Critical values of the compressive force applied to the panel .*

δ [mm]	P_{max} - from FEM calculations [MN]	P_u - acc. Eq. (2) [MN]
2.5	0.646	0.657
5.0	0.624	0.587
7.5	0.600	0.537
10	0.567	0.500

As can be observed, an almost ideal conformance between the values of P_{max} and P_u acc. Hughes theory, occurs for δ = 2.5 mm. Along with δ increasing, P_u values become increasingly smaller than P_{max} value; the difference reaches 12% for δ = 10 mm. The Hughes theory provides conservative results useful for initial estimation of ultimate strength of the panels having the structure shown in Fig.1.

And, the P_u value experimentally determined for the panel with the initial deflection of ~7.0 mm amounts to about 0.77 MN, [3] and exceeds the value P_{max} for δ = 7.5 mm (0.600 MN) (from Table) by about 25%. The difference can be explained by the fact that the real value of yield strength of the material is greater than $\sigma_Y = 235$ MPa assumed for FEM calculations. Even if the yield strength is exceeded the applied steel is capable of transferring much greater stresses than those resulting from the σ – ε relationship assumed for FEM calculations (Fig.4).

In the experiment appears also some constraints against rotation around the transverse axis of the end cross-sections of the panel whereas in the FEM model the hinge support of the panel ends was assumed.

The forces P_{max} presented in Table are considerably smaller than the above given value of the theoretical force $P_E' = 0.800$ MN.

FINAL CONCLUSIONS

The FEM calculations and those performed by using the simple theory of rod longitudinal bending, proposed in [1], show that the influence of initial deflections of the panel on ultimate values of compressive force, is considerable (Table). The ultimate force values decrease along with the maximum initial deflection increasing. Simultaneously, the forces calculated in compliance with [1] are smaller than those calculated by using the FEM (except of the case of a small value of initial deflection, namely δ = 2.5 mm) and the difference increases along with the maximum initial deflection δ increasing, and it reaches about 12% for δ = 10 mm. Hence the simple theory acc. [1] is applicable for conservative estimation of ultimate strength of axially compressed panels.

It is characteristic that the time-consuming, non-linear calculations by using the FEM model also provide the conservative results even greater by about 25% as compared with the experimental ones. This can be explained by the fact that the σ – ε relationship of lowered values of σ was applied for the calculations, as well as by different conditions in supporting the panel's ends, those assumed for the FEM model and those really existing during the experimental tests.

NOMENCLATURE

t - plate thickness
ε - unit strain
ν - Poisson's ratio

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