THE EFFECT OF A FILLING MATERIAL ON THE LOCAL ULTIMATE STRENGTH OF AN ALL STEEL SANDWICH PANEL

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ABSTRACT

This paper deals with the research of ultimate strength of the all steel sandwich panels under concentrated local loading. The research has been done in Ship Laboratory of Helsinki University of Technology. The research includes laboratory strength tests, numerical FEM analysis and design formulations for sandwich panels. Panel geometries, which have been analysed, are I-panels with straight webs and V-panels with inclined cores. The phenomenas, which have been studied, are the plastic collapse of sandwich panel's web and the permanent deflection, which occurs on sandwich panel's top plate. The aim of the study is to develop formulations to predict the failures when the sandwich panel is filled with foam. The development of the formulas has been carried out, by using Winkler foundation assumptions for the sandwich panel's filling material. FE-model has been used to find out the Winkler foundation characteristics.

INTRODUCTION

The demand for lighter structures in ships and also other moving vehicles has increased the demand for efficient structural arrangements. Structures can be made lighter by changing the material, the structural arrangement or both of these (Kujala, 1998). In ship structures steel has been used because of it's good material properties, such as fatigue, weldability,

ULTIMATE STRENGTH UNDER LOCAL LOADS

Available Design Methods for Empty Panels

Plastic Collapse of the Webs of the Sandwich Panel

Roberts (1983, 1997) has investigated failure of I-beams under concentrated loading. Using the assumptions, shown in Figure 1, he has determined an energy equation by calculating the work done by the external force and the work done by plastic moment in plastic hinges. The energy equation becomes

$$P_u \cdot \delta v = \left(4 \cdot \frac{M_f \cdot b_f}{\beta} + 4 \cdot \frac{M_w \cdot \beta}{\alpha \cdot \cos\theta} + 2 \cdot \frac{M_w \cdot c}{\alpha \cdot \cos\theta} - 2 \cdot \frac{M_w \cdot \eta}{\alpha \cdot \cos\theta} \right) \cdot \delta v \,, \qquad (1)$$

where P_u is the ultimate load, δv is the distance in force's direction which the force moves and α, β and θ are geometrical parameters which determine the shape of the deformed structure, c is the loading length at the web and η is the part of the web which does not carry any plastic moment, because it has yielded in compression before the yield lines have been formed. M_f and M_w are the plastic moments in the flange and in the web. θ is angle, which is assumed to be in the web due plastic mechanism.

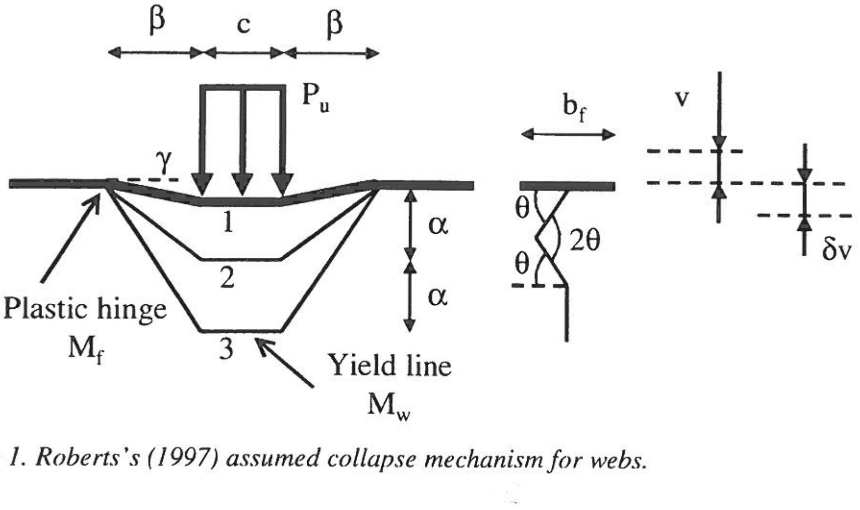

Figure 1. Roberts's (1997) assumed collapse mechanism for webs.

$$P_u = \left(4 \cdot \frac{M_f}{\beta} + 4 \cdot \frac{M_w}{\beta} \cdot \left(\frac{k_1 \cdot \beta \cdot c + \frac{M_f}{2 \cdot M_w}}{1 + k_1 \cdot A_N \cdot t_w}\right)\right), \tag{5}$$

where

$$M_f = \frac{\sigma_f \cdot g_c \cdot t_f^2}{4} \qquad M_w = \frac{\sigma_w \cdot t_w^2}{4} \qquad I_f = \frac{g_c \cdot t_f^3}{12}$$

$$k_2 = \frac{M_f^2}{3 \cdot E \cdot I_f \cdot 4 \cdot M_w} \qquad \phi = \tan^{-1}\left(\frac{2 \cdot k_2 \cdot \sin^2 \alpha_c}{\sin^2 \alpha_c - k_2^2}\right) \qquad \beta = \sqrt{\frac{M_f}{4 \cdot M_w \cdot k_1}}$$

$$k_1 = \frac{\sigma_f}{40 \cdot t_c \cdot \sigma_w} \cdot \frac{\sqrt{\sin^2 \alpha_c - \sin^2 \phi}}{\sin \phi \cdot \cos \phi} \qquad A_N = \sqrt{\sin^2 \alpha_c + \frac{27}{4} \cdot \cos^2 \alpha_c}\ .$$

In Naar's formula g_c is the width of one section of the core, σ_f and σ_w are the yield strengths of flange and core and α_c is the core angle.

Permanent deflection

Naar (2000) developed a formula to calculate the permanent deflection of sandwich panel's top plate by assuming that the top plate acts like membrane. By this assumption the shear forces and bending moments have been ignored. The external load then carried by the membrane forces, (Fig. 2).

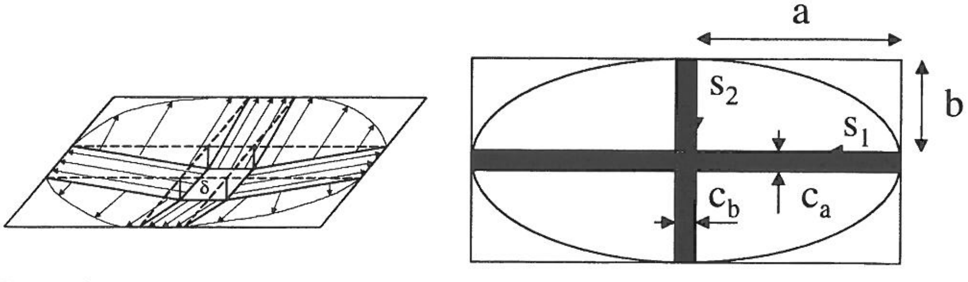

Figure 2. Naar's assumption of the deflection shape of the rectangle plate under local loading.

compression. The equivalent Young's (E_{eq}) modulus can be determined by energy assumptions, see Fig. 3.

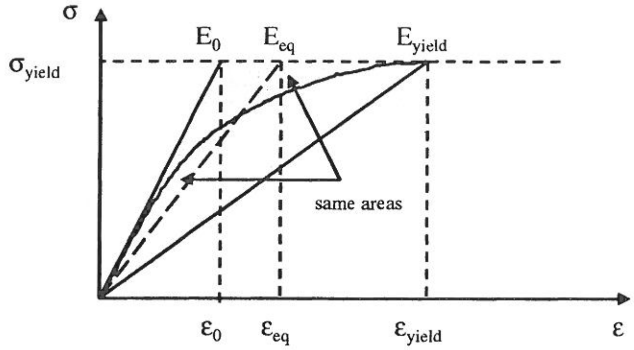

Figure 3. Stress-strain diagram of the filling material under compression.

The proper value for h_c can be determined by using 2D finite element model to calculate the stress distribution in the core material. The FE-model (Ansys 5.1) used consists of 2D-solid elements and beam elements. Beam elements were used to model the steel plates. 2D-solid elements were used to model the filling material. In the FE-model some initial deformation was given to web to get an accurate deformation shape for the web. After the direction of initial deformation was determined, Young's modulus was given to the compressive side and to the tensile side of the filling material. An elastic analysis was used to determine the stress distribution in the direction of support from the filling material to web. An example of this kind of stress distribution is shown in Fig. 4. From this stress distribution, the equivalent core height can be calculated by using for example Simpson II integration rule, from which the core height becomes

$$h_c = \frac{3}{8} \cdot \frac{s \cdot (\sigma_1 + 3 \cdot \sigma_2 + \ldots + 3 \cdot \sigma_{n-1} + \sigma_n)}{\sigma_{avg}}, \qquad (10)$$

where s is the spacing between the integration points and $\sigma_1 \ldots \sigma_n$ are the ordinates of the stress distribution. The σ_{avg} is the average stress from the stress values $\sigma_1 \ldots \sigma_n$.

$$E_x = \frac{\alpha^2 \cdot (k_{c,c} + k_{c,t})}{6} \cdot (3 \cdot c + 2 \cdot \beta) \cdot \delta v \,, \qquad (11)$$

where $k_{c,c}$ and $k_{c,t}$ are the compressive and tensile foundation modulus and α, β and c are geometrical parameters, which define the shape of the damaged web. This energy includes both the work done in the compressive and tensile side of the filling material in x-direction, see Fig. 5.

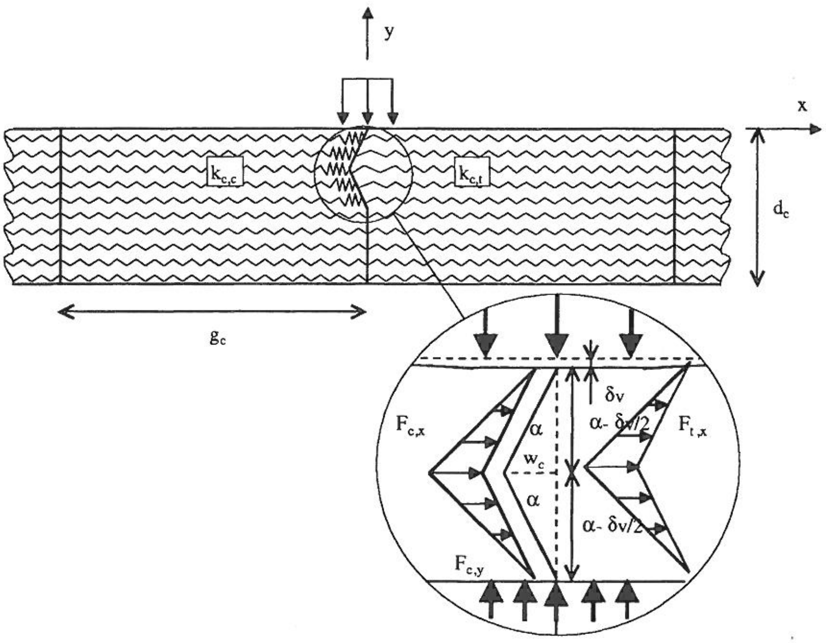

Figure 5. Reactions in the filling material caused by the external loading.

The filling material crushes under the deformed flange and the work done by crushing in y-direction, see Fig. 5, is equal to (Romanoff, 2000)

$$E_{c,y} = \sigma_{yc,c} \cdot \frac{\pi}{12} \cdot \left(3 \cdot c^2 + 6 \cdot \beta \cdot c + 4 \cdot \beta^2\right) \cdot \delta v \,, \qquad (12)$$

where $\sigma_{yc,c}$ is the compressive yield stress of the core material, α, β and c are geometrical parameters, which define the shape of the damaged web.

$$P_u = \left(4 \cdot \frac{M_f}{\beta} + 4 \cdot \frac{M_w}{\beta} \cdot \left(\frac{k_1 \cdot \beta \cdot c + \frac{M_f}{2 \cdot M_w}}{1 + k_1 \cdot A_N \cdot t_w} \right) \right) \cdot \left(1 - \left(\frac{\sigma_b}{\sigma_w} \right)^2 \right)^{0.5} \tag{15}$$

$$+ \sigma_{yc,c} \cdot \frac{\pi}{12} \cdot \left(3 \cdot c^2 + 6 \cdot \beta \cdot c + 4 \cdot \beta^2 \right) + \frac{\alpha^2 \cdot (k_{c,t} + k_{c,c})}{3} \cdot (3 \cdot c + 2 \cdot \beta) + P_{shape},$$

Permanent deflection

In the development of the formulae for ultimate load of the top plate of the sandwich panel, a Winkler foundation was assumed. In addition, it was also assumed that the web, right next to the loaded plate strip, could deflect in the direction of the top plate's membrane forces, see Fig. 6. The relation between the permanent deflection and loading becomes

$$F_t = c_{\text{support}} \cdot \left(2 \cdot \sigma_y \cdot t \cdot \left(\frac{c_a}{a_c} + \frac{c_b}{b_c} + \frac{\pi}{2} \right) + k_{c,c} \cdot (c_a \cdot c_b + a_c \cdot b_c) \right) \cdot \delta . \tag{16}$$

Where $k_{c,c}$ is foundation modulus of the filling material in the panel. The other constants are

$$\begin{cases} a_{\min} = \sqrt{2 \cdot \frac{\sigma_m \cdot t \cdot c_a}{k_{c,p} \cdot b}} \\ a_c = a_{\min}, a_{\min} \leq a \\ a_c = a, a_{\min} \geq a \end{cases} \qquad c_{\text{support}} = \frac{1}{1 + \frac{k_{1,1}}{k_{1,2} + k_2}} \qquad k_{1,1} = 2 \cdot \frac{E \cdot t_f}{g_c} \qquad k_{1,2} = \frac{E \cdot t_f}{g_c}$$

$$\begin{cases} b_{\min} = \sqrt{2 \cdot \frac{\sigma_m \cdot t \cdot c_b}{k_{c,p} \cdot a}}, \\ b_c = b_{\min}, b_{\min} \leq b \\ b_c = b, b_{\min} \geq b \end{cases}$$

Empty I-panels: $k_{2,i} = \frac{E \cdot t_w^3}{4 \cdot d_c^3}$

Filled I-panels: $k_{2,i} = \frac{k_{c,p}}{\lambda} \cdot \frac{\cosh^2(\lambda \cdot d_c) + \cos^2(\lambda \cdot d_c)}{\sinh(2 \cdot \lambda \cdot d_c) - \sin(2 \cdot \lambda \cdot d_c)}$

where: $\lambda = \sqrt[4]{\frac{3 \cdot k_{c,p}}{E \cdot t_w^3}}$

$$k_2 = \frac{P}{w}. \qquad (19)$$

For filled V-panels the determination of k_2 is very difficult and it has been considered that k_2 is the same for filled and empty panels.

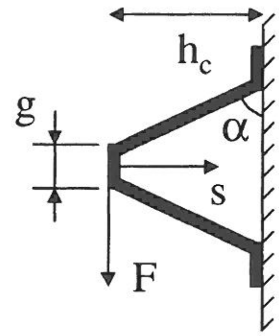

Figure 7. The co-ordinate system used in the determination of the stiffness of the V-panel's web.

Description of the Laboratory Experiments Used to Verify the Design Methods

Some laboratory tests were made to verify the formulas developed in the research. The test pieces made of steel used are shown in Fig. 8. The arrangement of the laboratory experiments is shown in Fig. 9.

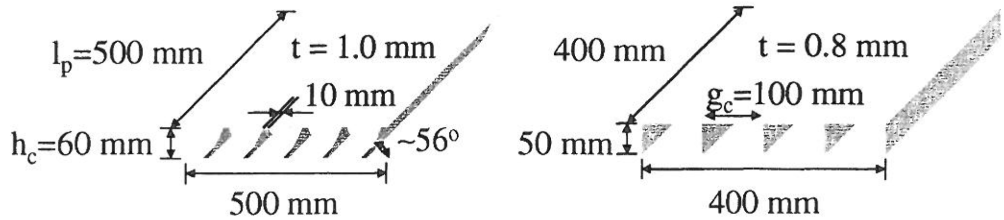

Figure 8. Panels used in the test program.

By changing the diameter of the patch load, the loading length of the web could be varied. To find out the behaviour of the top plate of the sandwich panel under loading, the distance (g_c) between webs of the core was varied from 100 mm to 180 mm in I-panels. The panels

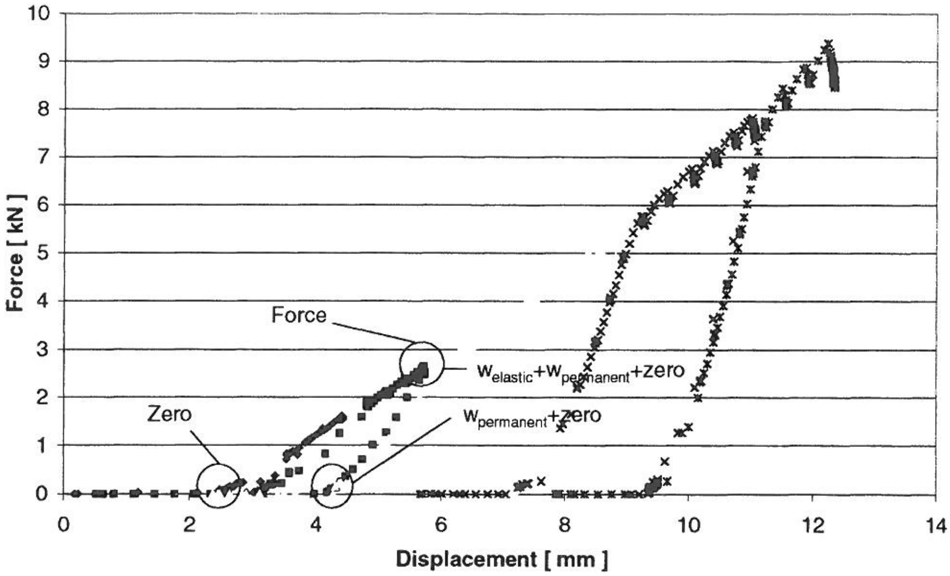

Figure 10. The determination of the permanent deflection.

Comparison of Laboratory Tests with Design Formulae

The calculations of the collapse load of the web were carried out with the data obtained from the material tests. The margin for error was determined with the total differential of the formulae developed for the collapse load. The plastic collapse load of the web for V-panel is shown in Fig. 11.

As can be seen in Fig. 11 and 12, the effect of a filling material on the plastic collapse load of an all steel sandwich panel, increases as the diameter of the patch load increases. Approximately the increase in weight per square-meter, caused by the filling, in I-panel is about 15%. The effect in collapse load is for 20mm patch load 20%, for 60mm patch load 60% and for 100 mm patch load 90%. Corresponding figures for V-panel are 10% increase in weight and 30% increase in collapse load for: the 20 mm patch load, 100% for 60 mm patch load and 140% for 100 mm patch load.

The comparison of the calculated and measured values for the permanent deflection, under loading is shown for I-panels in Fig. 13. As in collapse load calculations, the margin for error is determined by the total difference of the formulae developed.

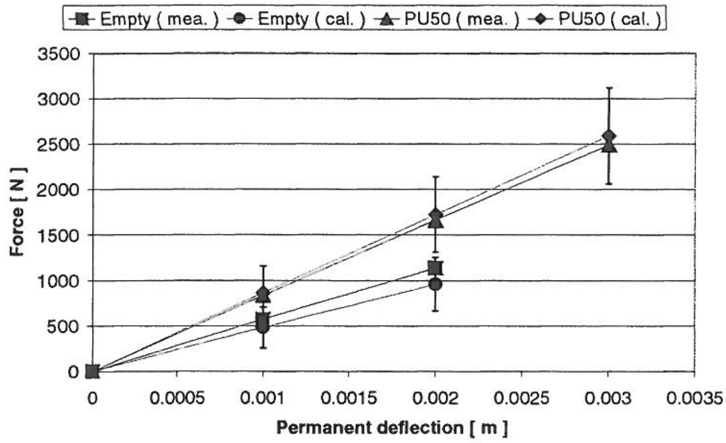

Figure 13. Permanent deflection vs. load, I-panel.

The effect of a filling material to the permanent deflection of sandwich panel's top plate is larger in I-panels than in V-panels. The reason for this is the lower stiffness of the I-panel's webs in the direction to top plates membrane stresses. The filling material increases the stiffness in this direction more in I-panels than in V-panels. The increase in the load, which can be carried by sandwich panel's top plate, is for I-panel with: 100 mm distance between the webs 50% and with 180 mm distance between the webs 500%. For V-panels the corresponding figure is for the distance of 100 mm 25%.

CONCLUSIONS

In this paper the work done in the development of the formulae to calculate the local ultimate strength of filled steel sandwich panels has been reviewed. The phenomena studied were, the plastic collapse of sandwich panel's the web plating and the permanent deflection of sandwich panel's top plate. The panels studied were I-panels with straight webs and corrugated core V-panels with inclined webs. The filling material has been assumed to act

LIST OF SYMBOLS

a	Longer edge of a plate
α	Parameter used in Roberts' formulations
α_c	Core angle
A_n	Naar's geometric parameter
b	Shorter edge of a plate
β	Parameter used in Roberts' formulations
c	Loading length
δ	Displacement
d_c	Height of the web
$\delta\theta$	Small rotation
δv	Small displacement
E	Young's modulus
ε	Strain
F_R	Roberts' constant (=1.45, for design purposes))
ϕ	Naar's geometric parameter
F_c	Resultant force due compression
F_t	Resultant force due tension
g	Width of V-panel's flange
g_c	Distance between the webs
η	Parameter used in Roberts' formulations
h_c	Height of the filling material
I	Second moment of area
k	Spring constant or foundation modulus
k_1	Parameter used in Naar's formulations
k_2	Parameter used in Naar's formulations
k_3	Parameter used in Roberts' formulations
M	Moment

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