FATIGUE STRENGTH OF PLATE PANELS WITH END-STRUTS

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ABSTRACT

Improving the strength of a thin plate panel subjected to uniaxial compression by adding a stiffener between the stiffener space is an impractical solution. Two end-struts welded in the plate panel have been proposed to increase the buckling and the ultimate strengths of the plate panel. However, high local stresses are developed in the vicinity of the end-struts locations. These stresses inevitably cause fatigue failure when the plate panel subjected to a cyclic load. In this paper, a fine FEM mesh is generated at the end-strut locations to precisely estimate local stresses. The influence of different end-strut shapes on local stress values is investigated to define the optimum end-strut shape which gives the minimum stress concentration factor. Based on this FEM analysis, the fatigue strength of the plate panel with different end-struts shapes using both S-N curves and damage factor concept can be accurately evaluated.

Keywords: End-struts, Stress concentration factor, Fatigue strength, Cyclic loads, S-N curve, Damage factor

NOMENCLATURE

a	Plate panel length /mm
a_s	End-strut length/mm
D	Damage factor
E	Young's modulus of elasticity, kg/mm^2
H	Height of the end-strut edge mm
f	Factor of safety
K_f	Stress concentration factor
m	The slope of the S-N curve
M-1	Model no. 1
N	Number of stress cycles to failure
N_o	Maximum of expected cycles
R	Curvature radius mm
S	Nominal stress range, kg/mm^2
S_o	Maximum stress range, kg/mm^2
t	Plate panel thickness, mm
t_s	End-strut thickness, mm
W_o	Initial deflection, mm
σ_{av}	Average acting stress , kg/mm^2
σ_{avc}	Average compressive stress , kg/mm^2
σ_{avt}	Average tensile stress ,kg/mm^2
σ_{max}	Maximum local stress, kg/mm^2
σ_y	Yield stress, kg/mm^2
Γ	The gamma function

INTRODUCTION

Utilizing higher strength steels of the material in plate panels leads to Lighter scantlings with the likehood of local plate buckling [1] and [2]. A new technique was suggested to prevent the occurrence of plate buckling under compression without increasing the numbers of stiffeners in the plate panel. Instead of adding a new stiffener between the stiffener space, two short end-struts are welded to the end of the plate panel in the same direction as the acting load [3]. The end-struts have two main functions. Firstly, they prevent the occurrence of buckling until the ultimate strength of the plate panel is attained. Secondly, the initial and the fabrication costs may be reduced due to the reduction in number of stiffeners. However, high local stresses are developed in the vicinity of the end-strut locations. These high local stresses have to satisfy the fatigue criterion as well as the yielding one. In this paper a fine FEM mesh around end-strut locations is generated to estimate the stress concentration factor [4]. The value of the stress concentration factor depends on both the end-strut shapes and the structural welding detail [5]. In this work, only the influence of different end-strut shapes on the magnitude of the stress concentration factor is considered. Then, the developed local stresses are checked with the allowable yield stress of the material to satisfy the yielding criterion. Here, the effect of the initial deflection and residual stresses is neglected when estimating the stress concentration factor.

Most recent damage failure reported in ships is associated with the crack initiated at stress concentration sites. Here, such sites, are the locations around the end-struts in the plate panel. Generally the fatigue strength at a point of a structure is measured by the magnitude of the acting stress range and the sustained number of cyclic load to failure. In this work, the fatigue strength at a point near to the end-strut edges is governed mainly by the number of loading cycles and the actual stress concentration factor. Here, the value of the local stress calculated by the FEM code is applied to estimate the fatigue life when the plate panel is subjected to either constant or random cyclic load. A selected S-N curve is applied for a constant cyclic load while the damage factor concept is adopted for a random load. Applying both concepts on plate panels. with different end-strut shapes, the fatigue strength may be accurately evaluated.

MODEL OF ANALYSIS

The object of this section is to generate a fine FEM mesh for evaluating local stresses and the stress concentration factor. These dimension of the plate is assumed to be 1000x1000x10 mm and the end-strut length "a_s" is taken 30% of the plate length "a". The end-strut of a flat bar section is considered with a height to thickness ratio "h_s/t_s" equal to 10. These dimensions are selected to prevent the occurrence of buckling [3]. The magnitudes of the yield strength and Young's modulus are equal to 25 kg/mm^2 and 21000 kg/mm^2, respectively. The plate panel is assumed to be simply supported at its ends and subjected to uniaxial average displacement of about 0.34 mm along the x-direction. Due to the symmetric behavior of the plate panel under this load, the FEM model of analysis is selected as shown in Figure 1. Then a fine FEM mesh is generated at locations of high local stresses. These locations are particularly selected near to the end-strut edges because, welding defects will inevitably occur and the possibility of failure is high [6]. In this model , the total used elements and nodes are 386 and 460 respectively.

As discussed before, the value of stress concentration factor is influenced by end-strut shapes. Therefore, three typical end-strut shapes with different edges are adopted. These are as follows :

M-1:The end-strut has a rectangular shape with a height at the edge = 100mm, Figure1-a

M-2:The end-strut has a snipped shape with a height at the edge = 25 mm, Figure 1-b.

M-3: The end-strut has a round shape with a height at the edge = 25mm and a curvature radius = 300mm, Figure 1-c.

The cutting operation and welding processes requirements are considered when selecting these models [7].

STRESS CONCENTRATION FACTOR

Applying the end-struts technique in plate panels has different purposes. Firstly, increasing the average buckling and the ultimate strengths beyond the yielding criterion. The average buckling and ultimate strengths have been calculated and checked in a previous work [3]. Secondly, keeping the fatigue strength value the same as required in plate panels without end-struts. In other words, the high local stresses developed in the vicinity of the end-strut edges have to satisfy the fatigue criterion as well as the yielding one. As discussed in the preceding section, a fine FEM mesh was generated near to the end-strut edges to accurately calculate the developed local stresses.

Figure 2 shows the stress distribution of the plate panel with different end-strut shapes and subjected to the load mentioned above. It is clear that the minimum stress value is widely distributed toward the top of the end-strut plane. While the maximum stress distribution is confined to the lower edge of the end-strut at the connections of the end-struts with the plate panel. This value of the maximum local stress is mainly dependent on the shape of the end-strut edge. Usually, this stress is expressed by the stress concentration factor, K_f at the edge of the end-strut. The

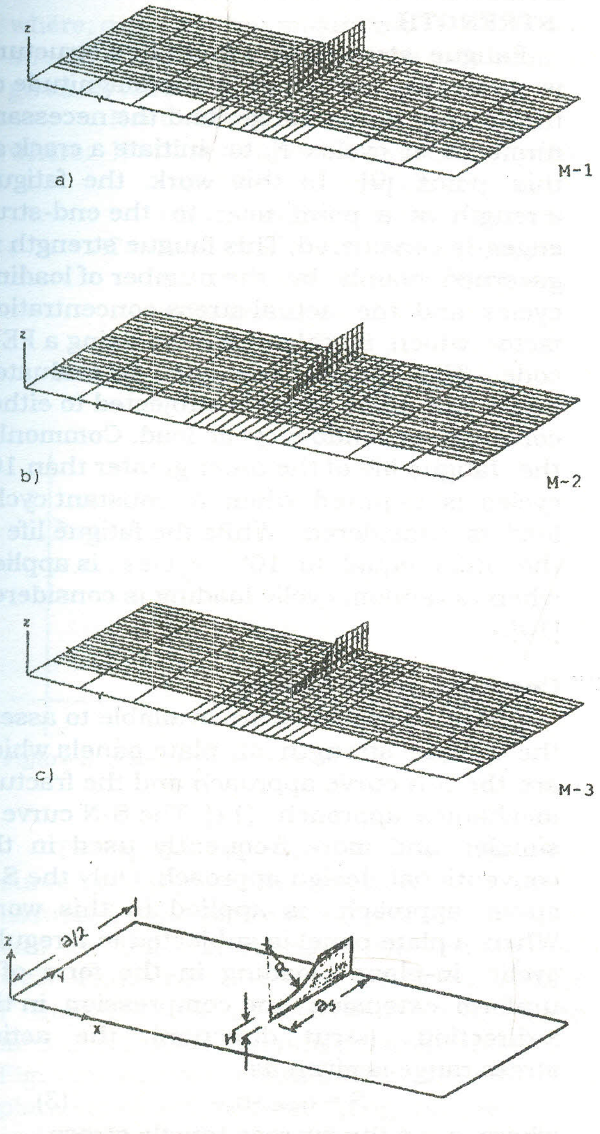


Figure 1 Mesh division of the plate panel with end-struts

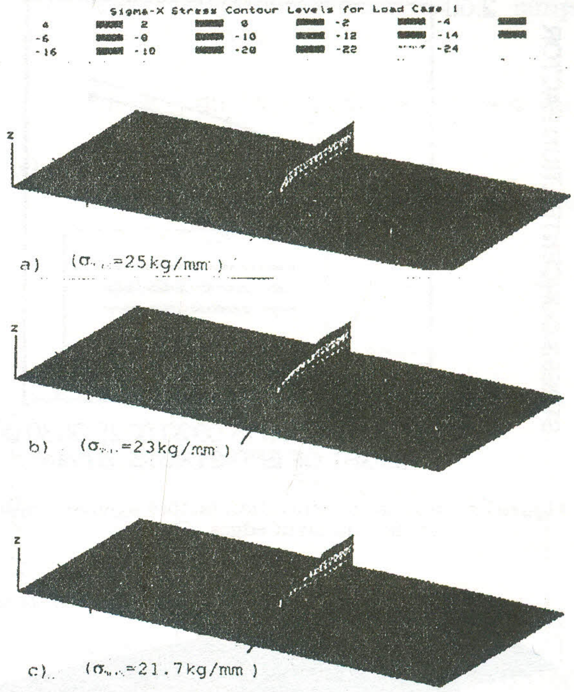


Figure 2 Stress distribution of the plate panel with different end-strut shapes

stress concentration factor, K_f is determined by dividing the stress value at the end-strut edge by the average stress at the plate end as follows [8]:

$$K_f = \sigma_{max}/\sigma_{av} \qquad (1)$$

where, σ_{av} is the average acting stress measured at the plate end under the applied axial displacement, while σ_{max} is the maximum developed local stress at the end-strut edge.

In Figure 2 the stress concentration factor reaches a maximum value of 2.1 (σ_{max}=25kg/mm^2) using M-1 shape, while this value is slightly reduced to about 1.9 (σ_{max}=23kg/mm^2) when the end-strut has the M-2 shape. In the case of the end-strut having the shape M-3, the stress concentration factor approaches 1.8 (σ_{max}=21.7 kg/mm^2). To achieve an additional reduction in the stress concentration factor using the M-3 shape, the height of the end-strut edge and the curvature radius are to be changed necessarily. As the height of the end-strut edge and the curvature radius become smaller, the stress concentration factor is greatly reduced as shown in Figures 3 and 4. A minimum value of the stress concentration factor equal to 1.4 could be attained if 6mm height and 200mm curvature radius are applied as shown in Figure 3. Here, stresses in the end-strut and the plate are redistributed. The high stresses region is transferred to the middle of the end-strut plane near to the plate end. This makes it possible to shift maximum stress distribution from the end-strut edge to the middle of the end-strut plane.

After the maximum local stress has been evaluated at the end-strut edges, it is preferred to check this stress against the yielding criterion. That is:

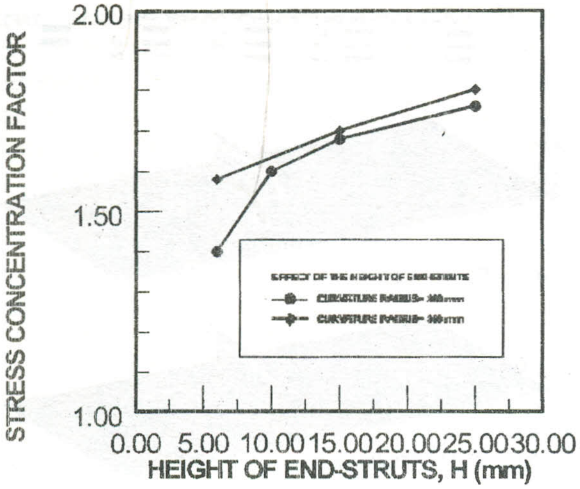
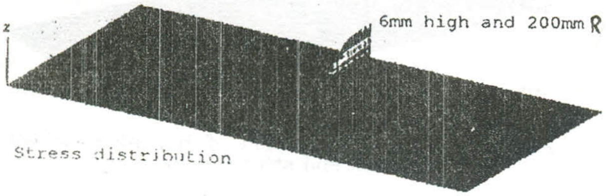


Figure 3 Stress concentration factors against heights of the end-strut edges



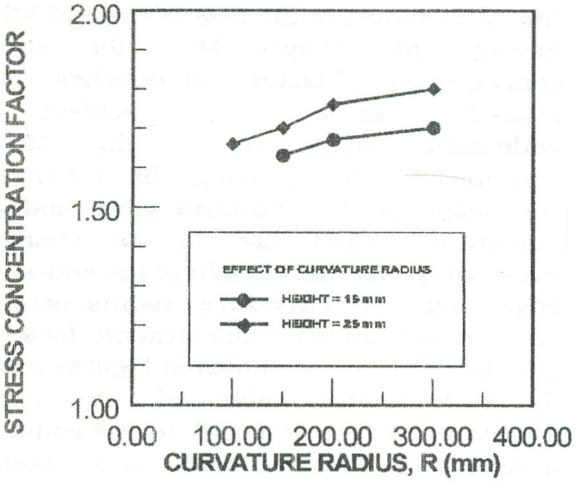


Figure 4 Stress concentration factors against curvature radius of the end-strut

$$\sigma_{max} = \sigma_o / f_s \qquad (2)$$

where, σ_{max} =the maximum local stress

σ_o =the yield stress of the material

f_s =a suitable factor of safety based on the yield criterion.

EVALUATION OF THE FATIGUE STRENGTH

Fatigue strength at a point in a structure is generally measured by the magnitude of the acting stress range and the necessary numbers of cycles N to initiate a crack at this point [9]. In this work, the fatigue strength at a point near to the end-strut edges is considered. This fatigue strength is governed mainly by the number of loading cycles and the actual stress concentration factor which is calculated by using a FEM code. The fatigue strength is evaluated when the plate panel is subjected to either constant or random cyclic load. Commonly, the fatigue life of the order greater than 10^5 cycles is required when a constant cyclic load is considered. While the fatigue life of the order equal to 10^8 cycles is applied when a random cyclic loading is considered [10].

Constant cyclic loading

Two approaches are available to assess the fatigue strength of plate panels which are the S-N curve approach and the fracture mechanics approach [11]. The S-N curve is simpler and more frequently used in the conventional design approach. Only the S-N curve approach is applied in this work. When a plate panel is subjected to a regular cyclic in-plane loading in the form of a uniform extension and compression in the x-direction (strut direction), the acting stress range is given as:

$$S = \sigma_{avc} - \sigma_{avt} \qquad (3)$$

where, σ_{avt} = the average tensile stress

σ_{avc} = the average compressive stress

Practically, the whole stress range, S is considered if the plate panel is initially stressed with the residual stresses. However, in the case of a perfect plate panel, the compression stage does not contribute to the fatigue strength which tends to close the opening crack [11]. Therefore, only the tension stage has the main contribution to the fatigue strength. Here, The tension stage is taken equal to the maximum local stress developed near to the end-strut edges. Therefore, the above equation is rewritten as follows:

$$S = \sigma_{maxt} \qquad (4)$$

where, σ_{maxt} = the maximum local tensile stress. The usual S-N curve equation is given as follows [12]:

$$N = C\ S^{-m} \qquad (5)$$

where: N = The fatigue life expressed by the number of cycles at failure under constant stress range S.
C = the value of N at the intersection of the S-N curve with the N-axis, as shown in Figure 5.
m = the slope of the S-N curve
S = the stress range at a point.

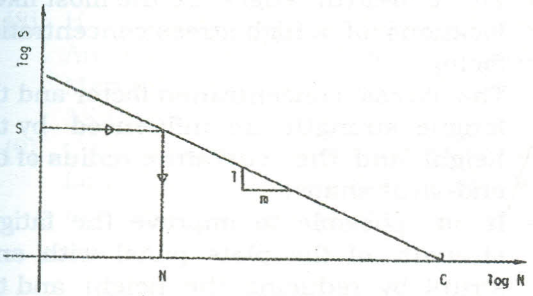


Figure 5 Schematic representation of S-N curve

To apply Equation 5, a suitable S-N curve is adopted. The selected S-N curve is assumed representing the practical welding and loading conditions of the plate panel with end-struts. Here an S-N curve of class F from DNV is adopted with $C = 10^{11.8}$, and m=3 to calculate the fatigue strength [12]. Figure 6 shows the fatigue life, N for the plate panel with different heights of the end-strut edges. In this figure, a maximum fatigue life equals to 1.2×10^5 is attained when 6mm height and 200mm curvature radius of the end-strut edge are used. Figure 7 shows the effect of the different curvature radii on the fatigue life N.

Random cyclic loading

When the fatigue strength of a plate panel subjected to a random cyclic load is dealt with, it is assumed that the total number of random cycles N_o is of the order equal to 10^8, with a certain probability density function considered [12]. In this study, Miner's damage factor is adopted which links between the random loading and the constant loading in a simple formula as fol -lows [13]:

$$D = \int_0^\infty dn\,/N = \int_0^\infty (dn\,/dS)(1/N)d \qquad (6)$$

where, D = the damage factor
dn= the number of cycles at a stress range S

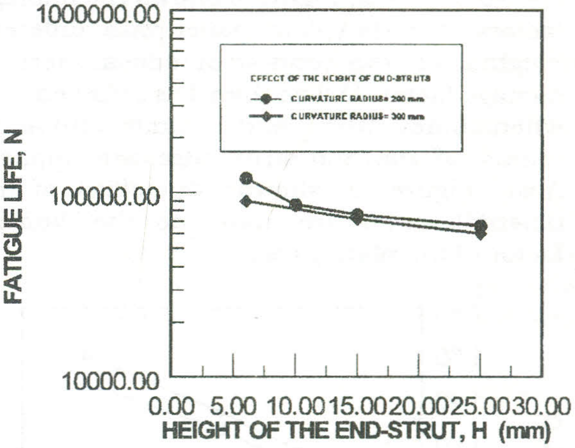


Figure 6 Fatigue life N against heights of the end - strut edges

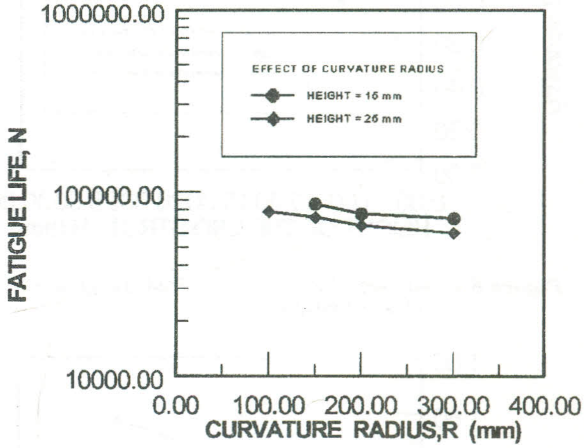


Figure 7 Fatigue life N against curvature radius of the end-strut

N = the number of cycles at failure under S.
dn may be expressed as an exponential function as follows:

$$dn = (N_o/\lambda)e^{-s/\lambda}\ ds \qquad (7)$$

where: λ is a scale parameter of the function.

The damage factor equation may be rearranged as follows:

$$D = (N_o/c)(S_o^m/\{\ln N_o\}^m)\ \Gamma(1+m) \qquad (8)$$

where, Γ = the gamma function
$N_o = 10^8$ cycles.
S_o = the maximum stress range that occurs once in 10^8 cycles.

Here, the limiting design value is,

$$D \leq 1 \qquad (9)$$

Similarly to apply Equation 8, the S-N curve of class F from DNV is adopted with $C= 10^{11.8}$, $m=3$. Figure 8 shows the damage factors for the plate panel with different heights of the end-strut edges. Here, a damage factor, D less than 1 is attained when 6mm high and 200mm curvature radius of the end-strut edge are applied. Also, Figure 9 shows the effect of the different curvature radii on the damage factor of the plate panel.

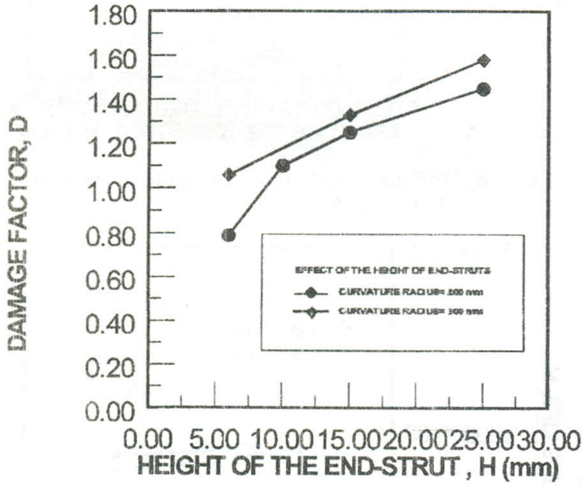


Figure 8 Damage factor D against heights of the end-strut edges

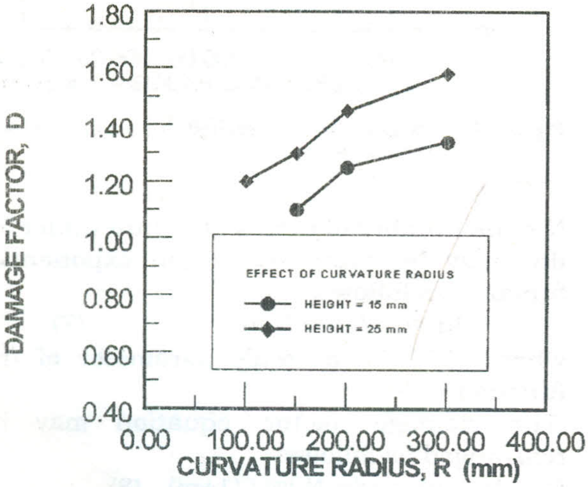


Figure 9 Damage factor D against curvature radius of the end-strut

CONCLUSIONS

A new technique was suggested to prevent the occurrence of the plate buckling by adding two end-struts in the middle of the end of plate panels. However, high local stresses are developed in the vicinity of end-strut edges which inevitably lead to fatigue failure. A fine FEM mesh near to these locations is generated to calculate the developed local stresses. The influence of different end-struts shapes on the stress concentration is investigated to improve the fatigue strength. From this analysis, the following conclusions are drawn:

1- The end-strut edges are the most likely locations of a high stress concentration factor.
2- The stress concentration factor and the fatigue strength are influenced by the height and the curvature radius of the end-strut shape.
3- It is possible to improve the fatigue strength of the plate panel with end-struts by reducing the height and the curvature radius of the end-strut edges.

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