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The ultimate and collapse response of cracked stiffened plates subjected to uniaxial compression

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ABSTRACT

Cracking damage in a stiffened panel is likely to have a deleterious effect on its ultimate strength and collapse characteristics. The present study examines this problem for a crack with different configurations and increasing length inserted in a stiffened plate. The cracks are positioned normal to the direction of the prescribed axial compression and crack propagation is not considered. A key feature of this work is the role of crack closure on the structural response. The ultimate strength reduction and collapse response are reported for stiffened plates of varying aspect ratio. Finally, an FE modeling approach is presented, which has the potential to extend this investigation to multi-bay panels at a reasonable computational cost.

1. Introduction

Many steel plated structures are stiffened through a combination of longitudinal girders and transverse cross frames with additional strengthening being provided by continuous equally spaced longitudinal stiffeners, usually having approximately the same size. The structural element between the intersecting girders and cross frames is often referred to as a stiffened panel or a bay. Current ship design practice requires that the ultimate limit state, or the ultimate strength, of the hull girder is evaluated and checked against specific design criteria [1]. The main load component for a number of parts of the hull structure, such as the deck and the bottom structure, is axial compression. Accordingly, the ultimate strength of a stiffened panel subjected to uniaxial compression is important both because its collapse load can act as an indicator of the hull girder strength, and also because a stiffened panel can be considered as a structural "unit" whose load-end-shortening response is directly used in the evaluation of the ultimate strength of the hull girder.

It is well recognized that a primary source of damage in many steel structures, in addition to corrosion, is fatigue cracking which effectively initiates from the first day of service. In the hull structure cracking damage is usually found in the welded regions, such as the weld intersections of the longitudinal stiffeners, girders and cross frames. Cracks do not represent necessarily an immediate danger to the structural integrity of a ship, even if during routine inspection many cracks are discovered. The hull structure exhibits considerable redundancy and loading can be transferred to adjoining non-cracked members aided by structural steels with high fracture toughness and ductility [2]. Although fatigue cracking is usually addressed as a fracture mechanics problem, in the context of a residual strength assessment it is also important to understand the effect of a crack on the collapse response of a cracked member under monotonic loading and hence to evaluate the reduction in ultimate strength. In the longer term this understanding is expected to contribute in the formulation of standards to assess the structural integrity of ageing structures.

There have been a number of studies concerning the influence of cracks on the load bearing capacity of structures, however the majority of them concern the elastic buckling behavior of cracked plates, for example [3–5]. The ultimate strength characteristics of cracked plates under axial compression or tension have been studied experimentally and numerically by Paik et al. [6]. More recently, Paik and Kumar [7] investigated the ultimate strength of a specific two-bay plate- (single) stiffener combination with cracking damage also subjected to axial tension or compression. These results of Paik and co-workers were also presented and reviewed in [8]. An important issue in the analysis of cracked panels subjected to compression is the role of crack closure since, when the crack faces come into contact, the structure stiffens and this will influence its ultimate strength and/or collapse response.

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Nomenclature

a	length of plate
b	width of plate
t_p	plate thickness
h_w	web height
t_w	web thickness
$A_p = bt_p$	cross-sectional area of plate
$A_w = bt_w$	cross-sectional area of web
c	crack length in plate
c_w	crack length in web
d	initial crack opening
E	Young's modulus
v	Poisson's ratio
σ_Y	yield stress in tension
$\varepsilon_Y = \sigma_Y/E$	yield strain
β_p	plate slenderness ratio
β_w	web slenderness ratio
w_p	plate imperfection function
w_{op}	maximum imperfection in plate
w_{os}	maximum imperfection in plate along the plate–web intersection
w_{web}	web imperfection function
U_{max}	maximum applied displacement on loaded section of stiffened plate
σ_{xx}/σ_Y	ratio of the average axial stress over the loaded end of the stiffened plate to the yield stress
$\varepsilon_{xx}/\varepsilon_Y$	ratio of the axially applied strain to the yield strain

This has only been addressed in [6] for cracked plate configurations under compression.

In the present study the ultimate strength and collapse response of cracked stiffened plates has been studied through a series of nonlinear finite element (FE) analyses using the FE code ABAQUS (versions 6.8 and 6.9) [9]. A number of crack configurations and lengths are considered, with the cracks located at the plate–web intersection, either in the plate or in both the plate and the web. This is motivated by the presence of the weld along these intersections, although the actual weld is not taken into account here. Cracks are likely to initiate also in other positions where weld interfaces are present, for example at the joining of two plate sections of a stiffened panel. The cracks are positioned normal to the direction of loading, i.e. subjected to Mode I loading, and extend through the thickness of the structure. Other crack orientations are of course possible, for example at an angle to the stiffener [6], however these are not considered in the work presented here. Moreover, any fracture mechanics related issues, such as the likelihood of crack propagation as the structure buckles and finally collapses, are not addressed. This represents a simplifying assumption that is likely to be less significant in the case where compressive loads are predominant [7]. In this respect, the selected crack configurations favor this assumption, however this issue is critically examined by means of the FE analyses.

The stiffened plates are subjected to uniaxial compression and a key feature of this investigation is the modeling of the contact region along the crack faces. Although shell elements are routinely used in the FE idealization of stiffened panels, the edge-to-edge contact of shells leads to certain geometric and solver limitations and, accordingly, solid finite elements were used in the modeling. The presence of a crack in the structure can be considered as a localized (material, geometric) imperfection and it is likely that the structural response will be sensitive to its characteristics, i.e. the crack position and length. Accordingly, the computation of the equilibrium response of the structure has been carefully examined paying attention to issues of mesh sensitivity, load incrementation and solver technique selection. This study has also investigated the ultimate strength reduction and collapse response of a cracked stiffened plate for a series of aspect ratios equal to 1, 1.5 and 3 (Table 1). It is recognized that the behavior of a stand-alone stiffened plate may not be in certain cases representative of a multi-bay structure strengthened by a number of longitudinal webs. This has been reported in the work of Hughes et al. [10], see also [11], for defect free panels. Accordingly, in the last section of this article, a modeling approach is examined using combined solid/shell elements which has the potential to address this extension to multi-bay panels at a reasonable computational cost.

2. FE modeling

2.1. Geometric data and material modeling

There are a number of key parameters that have to be considered when constructing the mathematical model of a cracked stiffened plate. These include the aspect ratio of the plate and web, their slenderness ratio, the location and inclination of the crack relative to the web, the extension of the crack to the web region and, finally, the ratio of crack length relative to plate width. The initial imperfections in the structure and the presence of residual stresses, either due to manufacturing or in-service operation, add to the complexity of the problem.

In the present work the problem is simplified by neglecting the presence of all residual stresses. It is further assumed that the material is at its virgin state and accordingly the effect of the cyclic loading, responsible for the initiation and growth of cracks, on the material response is neglected. This is usually an acceptable assumption when evaluating the ultimate strength of a structure since, prior to collapse, the overall loading in the structure does not induce widespread plasticity. Clearly in the vicinity of a crack the material response is far from its virgin state. Although this is not addressed here, it is likely to be a second order effect as far as the buckling and ultimate strength response of a cracked panel is concerned. Accordingly the emphasis here is on the effect of the crack geometry and no propagation was allowed.

The key geometric parameter in the present study is the plate aspect ratio, a/b, taken to be equal to 1, 1.5 and 3. According to Fig. 1, the length a and width b of the plate are, respectively, taken to coincide with the x and the y axes. The other dimensionless parameters that characterize the panel geometry were taken to be constant. In particular, the plate and web slenderness ratios are, respectively, $\beta_p = b/t_p\sqrt{\sigma_Y/E} = 2.064$ and $\beta_w = b/t_w\sqrt{\sigma_Y/E} = 0.344$, where t_p and t_w are the plate and the web thicknesses, respectively. In addition, the web to plate area cross-section area was kept fixed and equal to 0.25, a somewhat low value in order that the plate is the "dominant" structural member. These parameters are consistent with those used in a previous study of uncracked stiffened panels [12].

Table 1
Geometrical model data (dimensions in mm).

a/b	a	b	t_p	t_w	h_w
1	600	600	10	12.247	122.47
1.5	600	400	6.67	8.165	81.65
3	600	200	3.33	4.082	40.825