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Experimental studies on stiffened plates under in-plane load and lateral pressure

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ABSTRACT

An experimental study on stiffened plates subjected to combined action of in-plane load and lateral pressure is described in the paper. Details of the experiments and finite element analyses of the specimens tested are presented along with the results. Measurements of initial imperfection in the specimens have been made and included in the analyses. Results show that lateral load carrying capacity of stiffened plate drops with increase in axial load and vice-versa. It is found that plate slenderness ratio has significant influence on the ultimate load capacity of stiffened plates subjected to both in-plane load and lateral pressure. Increase of plate slenderness ratio results in a decrease of ultimate load capacity of stiffened plate. The accuracy of the finite element modelling is established by comparing the results with the corresponding experimental values.

1. Introduction

Plates stiffened in the longitudinal and transverse directions are commonly used to lighten the ship, aircraft and offshore structures. Stiffeners not only carry a portion of the load but also subdivide the plate into smaller panels, thus increasing considerably the critical buckling stress. The advantage of reinforcing a plate by stiffeners lies in tremendous increase of strength and stability with minimum increase of weight to the overall structures. Stiffened plates in marine and offshore structures are usually subjected to combined in-plane load and lateral pressure. For example, the bottom shell of the ship's hull is subjected to flexural compressive stress due to hogging bending moments and lateral water pressure. Under such combined loading, stiffened plates become unstable due to the presence of axial compression before the plastic flow can take place. Thus to predict the ultimate load-carrying capacity of stiffened plates, interaction between the in-plane load and lateral load must be studied completely. The stability of stiffened plates under various loading conditions has been a topic of interest for many years. Researchers have investigated the behaviour of stiffened plates either experimentally or numerically. Due to its complexity and many parameters involved, a complete understanding of all aspects of behaviour is not fully realized. Over the years, several codes and design recommendations for stiffened plates have been developed. However, it is found that no single code provides the most efficient guidance for the design of all structural components subjected to a whole range of loading. Hence, the experimental and analytical study on the strength of plates stiffened in both longitudinal and transverse directions and subjected to combined action of axial load and lateral pressure has become important.

Researchers, in the past, have developed different methods to analyse the behaviour of stiffened plates. They are generally based on orthotropic plate approach, discretely stiffened plate approach, strut approach or finite element and finite strip methods. Hoppman and Baltimore [1] used orthotropic plate approach to analyse simply supported orthogonally stiffened plates under bending and twisting. The stiffness of stiffened plates under static loading was determined experimentally. Huffington and Blacksburg [2] investigated the bending and buckling of orthogonally stiffened plate by conceptually replacing the plate-stiffener combination by an "equivalent" homogeneous orthotropic plate of constant thickness. This method was subjected to the limitation of the theory of thin homogeneous plates of constant thickness and also the ratio of stiffener rigidity to plate rigidity. Large deflection behaviour of stiffened plate subjected to static lateral load was examined by Soper [3] using the concept of equivalent orthotropic plates. The solution by Soper's method allowed for rotational constraint along the plate boundary. Okada et al. [4] used orthotropic plate approach to investigate the buckling strength of stiffened plates containing one longitudinal or transverse girder under compression.

Dean and Omid'varan [5] presented a study for analysis of rectangular plates reinforced by flat section stiffeners using a

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closed form field approach. Through a mathematical formulation for the analysis of eccentrically stiffened plates subjected to combined or separate actions of lateral and in-plane loading, Webb and Dowling [6] examined the effects of initial deformation and the use of hybrid plates. Geometrical non-linearity and material non-linearity were incorporated in the formulation. Kondo [7] presented an analytical study of the ultimate strength of longitudinally stiffened plates under axial load by beam-column theory. An elastic-perfectly plastic stress–strain relationship was assumed and was modified if necessary to take account of residual stresses. Findings by Ostapenko and Lee [8] established that a longitudinally stiffened panel subjected to lateral loading and axial compression behaves essentially as a beam column. Rayleigh Ritz finite element method was used by Tvergaad and Needleman [9] to analyse the buckling of eccentrically stiffened elastic-plastic panels on two simple or multiple supports. A comprehensive finite element program considering general loading conditions, material properties, geometry, boundary conditions and initial deflections was employed by Soreide et al.[10] for the analysis of stiffened plate in the ultimate limit state conditions.

The effectiveness of stiffeners against the ultimate strength of stiffened plates under in-plane loading was studied by Ueda et al. [11,12]. Behaviour of stiffened plates containing cutouts in the bed plates was examined analytically and experimentally by researchers [13–16] who studied the characteristics of local buckling of the stiffener web and their failure modes. Studies on imperfection sensitivity of wide integrally stiffened panel under compression [17] showed that wide panels are sensitive to geometrical imperfections when local buckling and overall buckling occur simultaneously. Smith [18] considered the elastic behaviour of stiffened plating subjected to lateral loading; the scope of his study was extended further to cover ultimate strength of stiffened plating under combined action of in-plane compression and lateral pressure [19]. Analytical methods to deal with stiffened steel panels under axial compression were developed [20,21]. Danielson et al. [22] studied buckling behaviour of stiffened plates subjected to a combination of axial compression and lateral pressure. Von Karman plate equations were used to model the plate and, beam theory was employed for stiffeners. Shanmugam and Arockiasamy [23] carried out experiments on longitudinally and transversely stiffened plates under combined loads. Stiffened plates simply supported on all four edges and subjected to combined action of axial and lateral loads were tested to failure. Bradford [24] presented a buckling analysis of longitudinally stiffened plates under bending and compression. Nonlinear finite element method was employed to determine the ultimate strength of stiffened panels subjected to biaxial compression and lateral loading [25–27]. The existing methods to predict the behaviour and ultimate strength of stiffened panels in marine structure were evaluated, examined and in some instances, the methods were developed further [28,29].

Experimental and analytical studies by Horne and Narayanan [30–32] provided guidelines for longitudinally stiffened flange plates used in bridge box girders. These guidelines formed the basis for bridge code BS 5400. Based on the strut approach Usami [33] proposed a method for computing the ultimate strength of stiffened box members in combined compression and bending. The computed results for simply supported stiffened plates in compression and bending were compared with finite element results. New design rules for stiffened plate structures under direct compression was presented by Johansson et al. [34]. Design methods for simply supported stiffened plates of high strength steel presented by Kitada et al. [35] included the design of stiffeners which behave as outstands. Design curves for ultimate strength obtained based on regression analyses were also given. Bijlaard's [36] method covers design of transverse and longitudinal stiffeners for stiffened plate panels. The analysis included two types of instability, instability of transverse stiffeners and torsional buckling instability of longitudinal stiffener of open cross-sectional shape primarily subjected to compressive load. In a series of investigations, Paik et al. [37–40] presented ultimate strength formulation of stiffened plates under different loading conditions. Failure modes of stiffened plates were categorized into six groups and panel ultimate strengths for all potential collapse modes calculated separately. It was found that the plate-induced failure mode based on Perry-Robertson formula predicts reasonably the panel ultimate strengths in a specific range of stiffener dimensions which follows the beam-column type collapse mode. More recent study on stiffened plates [41] addresses the issues related to the combined action of axial and transverse compression, shear force and lateral pressure and simplified numerical method to predict the ultimate strength given. Vibration characteristics of stiffened plates with cut outs and subjected to in-plane partial edge loadings have been studied [42] and buckling loads and vibration frequencies determined for different cut out ratios. Pan and Louca [43] has carried out both experimental and numerical studies on stiffened plates under extreme load cases such as hydrocarbon explosions. Parametric studies of a simplified model considering stiffeners under different stress state and loading levels have shown that boundary conditions, particularly, the in-plane restraints have a significant effect on the panel response under extreme loading cases.

The objective of this study is to investigate experimentally the behaviour of stiffened plates under combined action of in-plane compression and lateral pressure. In addition, numerical modelling using the finite element method, the accuracy of which could be established using the experimental results, has been carried out. It is expected that both the experimental and numerical studies would provide some insight into the behaviour of stiffened plates. Measurement is made to obtain the initial imperfection profile for the stiffened plate specimens tested. The measured imperfections are used in the finite element analyses so that the realistic behaviour of stiffened plates could be investigated. The numerical method is used to study a number of stiffened plates in order to examine the interactive effect of axial compression and lateral pressure on stiffened plates.

2. Experimental investigation

Twelve stiffened plate specimens subjected to in-plane load and uniform lateral pressure were tested to failure in order to examine the ultimate load behaviour and capacity. The specimens were divided into two groups, namely series A and series B with plate slenderness ratios (b/t_p) of 100 and 76, respectively. The behaviour of stiffened plates under combined in-plane load and lateral pressure was observed.

2.1. Fabrication and details of test specimens

The test specimens were fabricated using hot-rolled steel plating of Grade 50 which complied with BS4360. The base plates and stiffeners were first cut to the required size. To avoid any severe distortion and change of material properties, saw cut instead of flame cut were used. The specimens were formed by assembling the base plate and stiffeners in the specified locations. Longitudinal stiffeners were first attached to the base plate by means of tack-welding followed by welding of shorter sections of transverse stiffeners. Continuous welding was then carried out along the stiffeners. Sufficient time was allowed for cooling in order to minimize the effect of initial distortion caused by excessive heating and to keep the residual stress minimum. All