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Experimental and numerical analysis of plates quasi-statically loaded by a rectangular indenter

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A B S T R A C T

In this paper, a series of experiments are performed in order to examine the response of clamped steel plates loaded quasi-statically at their centre by a rigid rectangular indenter. Four types of boundary conditions, which offer varying levels of the supports flexibility, are investigated in the finite element modelling study. The numerical simulations showed that the predicted permanent deflections of the plate are very sensitive to the way in which the supports are modeled. Simplified boundary conditions are formulated in order to account for the actual support constraint. The deformation modes for plates with different aspect ratios are analyzed and a new mode, which is observed in plates with relatively large aspect ratio, is defined within the rigid-plastic mechanism analysis framework. It was shown that the numerical simulations can predict accurately the permanent deflections and deformation modes when appropriate boundary conditions are applied. The influences of the aspect ratio and plate thickness, on both the boundary conditions definition and in-plane displacements are discussed from further numerical studies.

1. Introduction

Plate is one of the basic structural components for ships and other marine structures. Ship plates are likely to be subjected to localised loadings, such as the wheel loads of vehicles or landing aircrafts. The structural behaviour of plating under such types of loading has been widely studied from the aspects of experiments, numerical simulations and simplified analytical methods.

One of the most important problem, which has drawn the researchers' attention is the correspondence between the boundary conditions in the experiments and their formulation in the numerical and theoretical models. It has been observed from the comparative experiments that the small in-plane movement resulted in larger deflections than those of a fully clamped plate and had a significant effect on the failure mode of the plate [1]. Based on the rigid, perfectly plastic model, it has been demonstrated that the in-plane displacements at the boundaries of a beam and a square plate led to larger transverse displacements of corresponding structures which are fully clamped [2]. Thus, it is important for engineers to know in detail

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the in-plane restraint at the boundaries, which can influence greatly the structural response and, in particular, the load-carrying capacity of plates.

With the use of numerical analysis, a series of investigations on boundary conditions of laterally loaded structures which are clamped [3–5] or welded [6,7] has been conducted by the research team of Prof. Guedes Soares. In their work, a rather complex modelling work was completed despite the assumed significant simplifications, in order to provide an accurate representation of the boundary conditions and obtain agreement with the experiments.

However, in order to get theoretical solutions of the influence of boundary conditions on the structural behaviour, simplified boundary conditions models should be established. The force-displacement curves of the single panel with edges free to slide inwards under uniform pressure which were studied experimentally by Clarkson [8], could be well predicted by the "kept straight" boundary condition models with the rigid, perfectly plastic assumption [2]. The in-plane restraint of the plate was approximated by using non-linear translational springs and a constant slippage allowance at the boundaries, to predict the deflections of tested square plates under pulse pressure loadings in the elastic-plastic theoretical model [9]. Thus, combined with the similar assumptions adopted in theoretical studies, an alternative simpler and more convenient modelling method is possible to define proper boundary conditions of the tested structures.

Despite the dynamic characteristics of marine structures subjected to abnormal/accidental lateral loads, the quasi-static analysis can be applicable to predict the behaviour of structures subjected to a low velocity impact by a heavy striker, as demonstrated in Ref. [10]. Taken as an example, in the case of the heavy landing of an aircraft or helicopter, the wheel loading is usually considered as an equivalent static load obtained by applying an appropriate impact magnification factor to the maximum take-off weight, in order to develop a rapid assessment of structural strength in the design of helicopter decks [11].

In this paper, in order to model a simplified wheel-to-ship deck collision scenario, a series of experiments on small-scale rectangular ship plates was conducted, which can provide a basic understanding for the dynamic characteristics of plating in terms of the deformation modes and the interaction forces. The plate specimens were clamped at four sides and loaded quasi-statically at the centre by a rectangular indenter.

Based on the experimental details, the boundary conditions were further studied numerically using the finite element package ABAQUS. An empirical parameter m was proposed to represent the various constraints on the translational degrees of freedom at the boundaries. It was found that with a proper value of m selected in the numerical simulations, a simple and appropriate boundary condition model can be formulated to provide satisfactory predictions of the response of plates in terms of the force-displacement response and deformed shape of the tested plates.

The influence of the aspect ratio and the plate slenderness on the structural behaviour was further explored based on a validated numerical model. Moreover, the relationships of the values of m and in-plane displacements at the boundaries with the two parameters were described with two simple functions, which is useful of the construction of a further theoretical framework.

2. Experimental details

A series of experiments was performed in order to gain further insight into the quasi-static behaviour of ship plates loaded by a rigid rectangular mass.

The plate specimens used in the tests were cut from high strength steel sheets with thickness (t) of 4 mm, 6 mm and 8 mm, respectively. The panel included one span between the web frames and one span between the longitudinals. The respective span lengths were 1200 mm and 350 mm. For comparison, another aspect ratio of $\alpha = L/B = 2$ was designed with the constant plate breadth.

The specimens were supported by 80 mm equally-spaced M8 bolts between two thick (40 mm) rectangular steel plates (upper and lower support plates), as shown in Fig. 1. The bolts compressed the specimen and restrict its in-plane displacement between the supports. In fact, the supporting plates and specimens were all connected with a strong structural base to prevent their movement. Although the structural supports were made of mild steel, it was assumed that they were stiff enough and did not suffer deformations during the test. A machine was used to provide the torque to screw the bolts and compress the supported length of the specimen during the experiments.

The indenter had a rectangular face of $s \times h = 299$ mm $\times$ 185 mm, whose dimensions were determined based on a typical wheel-on-deck interaction scenario. It was fabricated from high strength steel and the front rectangular part was strengthened by six brackets all around to avoid deformation during the loading process; its geometry is depicted in Fig. 2. The indenter was positioned at the mid-span of the specimen and screwed into the hydraulic cylinder with the in-built loading transducer.

A displacement transducer positioned under the plate as required was connected to the data acquisition instrument TMR-211. This enabled vertical deflections to be measured at the plate centre.

The quasi-static loading and unloading process was carried out to investigate the plate behaviour with different thicknesses and aspect ratios. The loading was applied by the MTS 322 test-frame servo-hydraulic test machine (25 ton) under load control at a rate of about 2.5 ton/min. The overall view of the test set-up is presented in Fig. 3. The loading process stopped when sufficiently large deflections of the plates were observed. Then the load was removed and the indenter departed from the plate.

In order to obtain the mechanical properties of tested materials, three standard static tensile tests for each plate thickness (t) were conducted on a material testing machine at average strain rates of approximately $4 \times 10^{-4}\ s^{-1}$ until fracture occurred.