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Simplified analytical method to evaluate tanker side panels during minor collision incidents

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ABSTRACT

The paper presents a simplified analytical method to examine the energy absorbing mechanisms of small-scale stiffened plate specimens, quasi-statically punched at the mid-span by a rigid indenter with a knife or a flat edge shape. To validate this method, experiments and numerical simulations are conducted on specimens scaled from a tanker side panel limited by one span between the web frames and the stringers. Therefore, the paper provides practical information to estimate the extent of structural damage within ship side panels during collision accidents. The experimentally obtained force–displacement responses and shapes of the deformation show good agreement with the simulations performed by the explicit LS-DYNA finite element solver. The numerical results manage to describe the process of initiation and propagation of the material fracture in the side panel specimens and provide detailed information of the energy dissipated by each structural component and its contribution to total energy during the entire deformation process. The analytical method derives expressions to estimate the relation between the plastic deformation and the energy dissipation of the stiffened plates. Both the plate and the stiffener elements dissipate the energy through rotation of the plastic hinges at the applied load and the support and the membrane tension over the plastically deformed region between the loading and the supports. The proposed simplified expressions give a good agreement with the experimental and numerical results.

1. Introduction

Increased attention has being paid to reduce the risk of oil spill due to collision and grounding accidents involving large tanker vessels, as reviewed, for example, in the latest research results and innovations presented by Amdahl et al. [1]. In the case of a collision, the absorbed energy by the struck ship at the moment of the inner hull rupture can be maximised with a strengthened double hull structure [2]. Therefore, the design of tanker double hulls requires an accurate prediction of the extent of damage in the structural components subjected to lateral impact, evaluating not only the worst case, but also other minor collision events that ships experience during service [3,4].

In order to assess the internal mechanics of ship structures during accidental events, empirical formulae, simplified analytical methods, finite element simulations and experiments are used. Since full-scale ship collision and grounding experiments are extremely expensive, they are rarely conducted [5–7]. Moreover, it is difficult to analyse the data obtained from such tests since the experimental measurements are influenced by many other variables of the complex ship structures and the external conditions surrounding the experiments. Hence, model laboratory tests are the most practical means for investigating the crashworthiness of ship structures. In most cases, the experimental impact response is examined by penetrating side or bottom panels using quasi-static lateral loads in order to obtain continuous records of the damage process and detailed information from each specimen. These types of tests have been used to propose analytical expressions for the primary damage mechanics [8,9] or to validate numerical analyses [10–13].

Nowadays, the finite element method is the preferred design tool for predicting the controlled failure, the maximum deformation, or the largest loading which can be sustained by a structure, commonly encountered in the analysis of structural crashworthiness in many fields of the industrial engineering. For example, complex finite element models of ship structures have been used to

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calculate the energy absorbed during collision and the extent of damage due to large in-plane and out-of-plane loadings in the hull structures [14–16]. However, as the numerical results should be validated with experimental tests before being implemented in the structural design, ship collision simulations are performed only for comparative purposes. In this respect, prior to performing analyses of large-scale structures, it is necessary to verify the experimental–numerical models of the large deformation in small-scale structural components [3,17].

The simplified analytical methods are based on the actual deformation mechanisms of structures and represent the most rapid tools to evaluate preliminary designs [18–27]. These methods establish the global pattern of deformation by adding up all local contributions of the individual structural components being capable of capturing the main features of the mechanical damage. Over 30 years ago various mechanisms of energy dissipation for ship structures subjected to collision loads were identified and described by Amdahl [18]. Afterwards, simple expressions relating the absorbed energy and the destroyed material volume were proposed [21,22]. Recently, simplified analytical methods to assess the energy absorption of ship structures were developed by analysing the plastic mechanism of individual structural members [24,27]. Reported investigations describe the deformation characteristics of ship structures in head-on collisions [18–20], side collisions [18,21–24] and groundings [25–27]. However, the failure of the material is still an issue for simplified analysis of complex structures, thus this phenomenon is mainly limited to ship plates describing in detail the cutting, tearing, folding, crushing, rupture and membrane stretching [18,22,28]. Although an empirical rupture strain was proposed by Paik and Pedersen [21] to predict the overall failure of full-scale structural members, it does not consider the stress concentration and the initiation of the crack.

The present paper is a continuation of the recent investigation reported by Villavicencio et al. [4]. They conducted finite element simulations of a small-scale tanker side panel specimen quasi-statically punched at the mid-span by a knife edge indenter, in order to represent a ship-to-ship collision scenario. The numerical analysis discussed aspects of particular relevance to the behaviour of ship structures subjected to accidental loads which could give rise to difficulties in interpreting finite element calculations. In particular, Villavicencio et al. [4] commented on the material nonlinearities, the importance of specifying the precise boundary conditions and the joining details of the structure. Here, the experimental and numerical results presented in Ref. [4] are compared with a new quasi-static test and simulations on a similar tanker side panel, this time punched by a flat edge indenter. More importantly, a simplified analytical method is presented to examine the energy absorbing mechanisms provoked by the quasi-static indenter–specimen interaction. The analytical method, validated with the experimental and the numerical results, derives expressions to estimate the relation between the plastic deformation and the energy dissipation of the stiffened plates.

The selection of this new type of indenter shape obeys to the recommendation given in Ref. [28] where it is stated that rational models for the bulbous bow should consider a flat tip on the wedge indenter. During service operation, a ship might be struck by another ship which could have a wide range of bow shapes. The geometry of the indenter strongly influences the plastic deformation and failure mechanisms of the struck ship. Therefore, the nose shape of the indenter is one of the most influential parameters for estimating the response of ship structures during collision incidents since it defines the contact area with the struck ship.

The actual finite element simulations provide detailed information of the initiation and propagation of the material fracture in the side panel specimens, and manage to describe the energy absorbed by each structural component and their contribution to total energy dissipated during the specimens' deformation process. The simplified analytical method to evaluate the energy absorption of the stiffened plates describes the deformation mechanism and the inner force individually for the plate and the stiffeners. Both the plate and stiffener elements dissipate the incident energy through the rotation of the plastic hinges at the applied load and the supports and the membrane tension over the plastically deformed region between the loading and the supports. Although the method evaluates the energy absorption of the stiffened plates, it disregards the material failure, and thereby comments on this highly nonlinear material aspect are given. The paper provides preliminary design tools to assess the internal mechanics of ship collisions and to develop crashworthy designs of double sided tankers' structural components. Moreover, the results of the present investigation could find practical application in further parametric analyses of the same or similar double hull structures subjected to large lateral deformation, including, for example, different scantlings or geometries of the indenter.

2. Ship collision scenario and experimental details

The experiments attempt to represent the collision scenario shown in Fig. 1. A rigid bulbous bow (striking ship) impacts the mid-span of a side panel unit (struck ship) limited by one span between the web frames and the stringers. In practice, however, it is impossible to represent a real collision scenario at the laboratory since there are a large number of parameters associated with the ship collision problem, such as the different ship types, structural arrangements, drafts, striking bows and, most importantly, the hydrodynamic effects of the added mass [29]. Here, the impact event illustrated in Fig. 1 is scaled and examined in a quasi-static manner. Therefore, various differences are found: the boundary conditions of the small-scale experiment should differ to the ones of the full-scale prototype; the quasi-static experimental loading condition should be different to the loading given by a real ship travelling at a low velocity; the experimental bow shapes are highly idealised. Nevertheless, the experiments provide a better understanding of the deformation process of tanker side panels during a collision event.

The experimental program evaluates the energy absorbing mechanisms and failure of two small-scale stiffened plate specimens quasi-statically punched at the mid-span by a rigid indenter. The test setup is presented in Fig. 2. The specimens represent a one-fifth scaled tanker side panel structure; the geometry is sketched in Fig. 3. The panels include one span between the web frames and

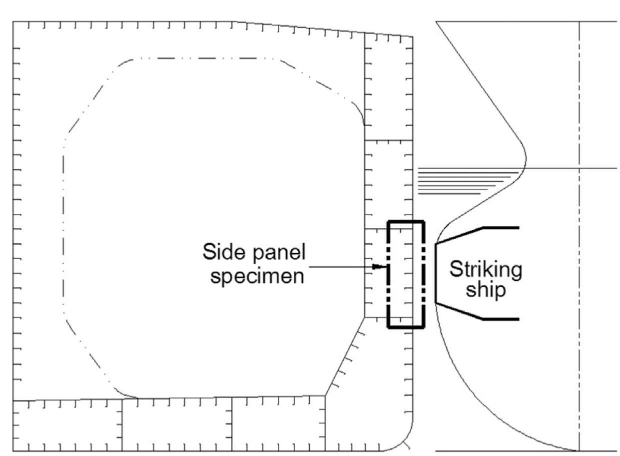

Fig. 1. Impact scenario on the full-scale prototype.