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Experimental and numerical penetration response of laser-welded stiffened panels

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ABSTRACT

Ductile fracture in large structures is often resolved with non-linear finite element (FE) simulations employing structural shell elements which are larger than localization zone. This makes solution element size dependent and calibration of material parameters complex. Therefore, the paper explores the ability of numerical simulations to capture the penetration resistance of stiffened panels after determining steel material fracture ductility at different stress states. The numerical simulations are compared with experiments performed with rigidly fixed 1.2 m square panels penetrated with half-sphere indenter until fracture took place. Response of the panels was measured in terms of indentation force versus indenter displacement. In parallel, tensile tests were performed with four different flat specimens extracted from the face sheet of panels to characterize the material fracture ductility at different stress states. Panel simulations were performed with two fracture criteria: one calibrated based on the test data from dog-bone specimen and other calibrated based on the data from all tensile tests. To evaluate the fracture criteria in terms of their capacity to handle mesh size variations, mesh size was varied from fine to coarse. Results suggest that fracture criterion calibrated based on the range of stress states can handle mesh size variations more effectively as displacement to fracture showed considerably weaker mesh size dependence.

1. Introduction

1.1. Background

Growing awareness of environmental risks related to storage and transportation of chemicals and fossil fuels provides strong incentive to develop impact and collision resistance structures. Thin-walled structures such as ships transporting hazardous substances are especially vulnerable to puncture due to the collision and grounding that constitute as the most frequent accident type [1]. Resulting chemical or oil spill poses a devastating effect on the marine ecosystem [2], but also involves high acute costs through clean-up operations especially in remote and sensitive areas [3] in addition to indirect effect to economic activities in the region [4].

While the pre-emptive risk management approaches and analyzes are the most effective means to combat the occurrence of these accidents [5–7], the performance of the ship structure during the accident determines the degree of seriousness and consequence. Therefore, understanding the whole damage process under localized loads and ability to simulate fracture in large thin-walled structures is a crucial step from mere assessment of structural failure, towards structures where material fracture is carefully engineered to occur in a desired, well controlled manner. Moreover, this understanding lends itself for successful holistic safety assessment procedure including post-accidental flooding simulation where size of the opening plays an important role [8,9].

Therefore, penetration resistance of stiffened steel plates has been extensively studied experimentally and numerically. Recent review by Calle and Alves [10] covering numerical material fracture modelling approaches in ship crash analysis highlights the high computational cost of the analysis and consequent restriction to large structural shell elements. While computationally efficient, the size of the large structural shell elements imposes restrictions on how the fracture initiation and propagation can be modelled in large structures [11]. When shell elements are used together with element erosion technique to represent fracture, the main challenge is to select the appropriate numerical fracture strain as it depends on the element size and stress state. For instance, benchmark analysis by Storheim et al. [12] where simulations and experiments of three different stiffened shell structures were compared showed that fracture criteria are in general not sufficiently accurate with respect to the stress-state and mesh dependence.

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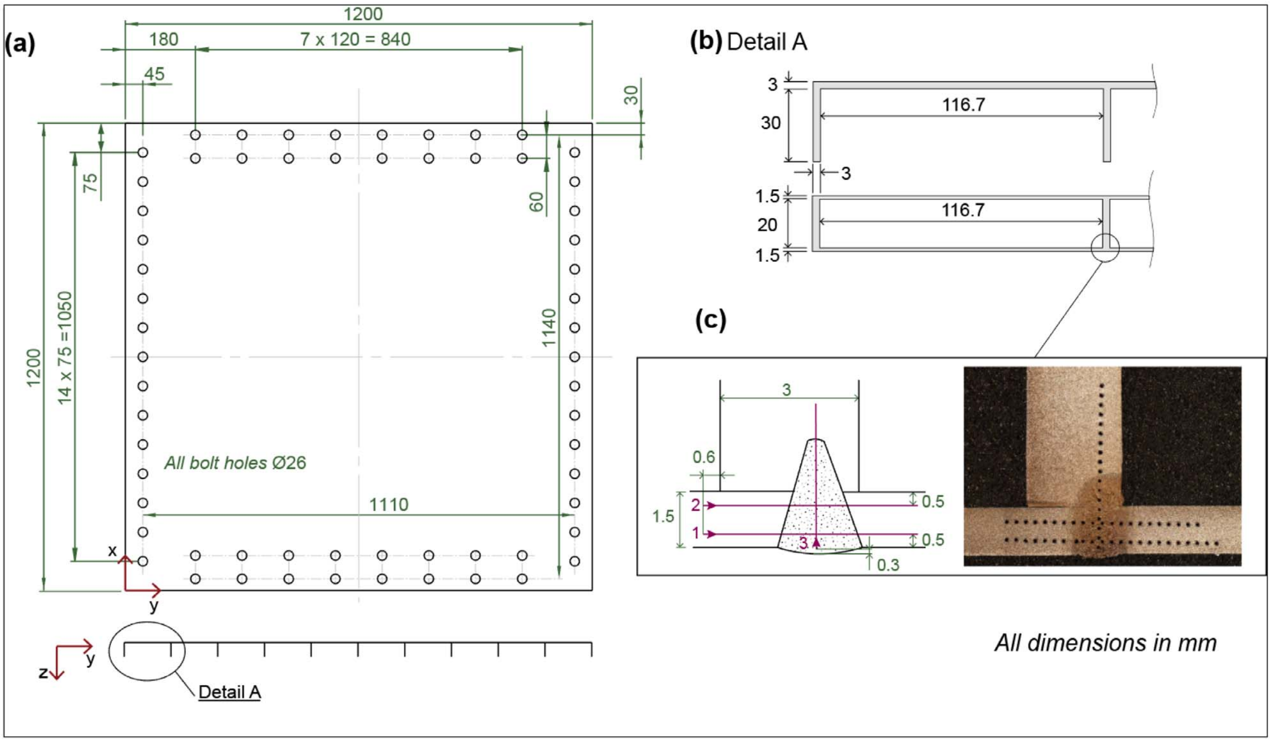

Fig. 1. (a) Geometry and dimensions of stiffened panel. (b) Cross-section of the stiffened panel and similar sandwich panel. (c) Detailed view of laser stake weld showing the three hardness measurement locations.

One factor that contributes to the large scatter in results is the lack of experimental data where both, material and structural behaviour, are readily available. Clearly, the full-scale ship collision and grounding experiments are invaluable in providing the insight to the whole collision process [13,14], but the high cost and difficulty of separating internal and external mechanics makes detailed damage and deformation mode assessment unreliable. Instead, structural tests with scaled structures are preferred where penetration resistance of structures is assessed in controlled laboratory environment, e.g. see the review by Calle and Alves [10] and more recent experimental-numerical investigations by Morin et al. [15] and Gruben et al. [16]. Although these tests map the most important failure modes observed in full-scale experiments, including the fracture under different stress states, accompanying tensile tests were performed only under uniaxial tension. Thereby, fracture strain used in simulations ignored the effect of stress state [17,18] or stress state effect was calibrated only based on uniaxial tensile test, e.g. [19,20]. Moreover, fracture strain sensitivity to element size (mesh size dependence) is also established based on the single stress state, although it is well established that mesh size dependence relates to the amount of strain localization prior to fracture and thus, depends on the stress state. Consequently, in these attempts to resolve fracture strain scaling based on a single stress state lead to inconsistent results with respect to discretization. While calibration based on single test is efficient and attractive especially in design practice, the objective of this work is to show the enhanced consistency, and thus reliability, of the FE solution when fracture strain and its element size sensitivity is calibrated based on different tensile tests.

Therefore, we experimentally determined the penetration resistance of laser welded stiffened steel panels deformed quasi-statically with rigid indenter and performed tensile tests that cover range of stress states. Stiffened panels are common structural elements in ship and offshore structures. Tensile tests were repeated at least twice to check the validity of the experimental set-up, and thus confirm the repeatability of the tests. Data acquisition in panel experiments comprised indentation force and displacement of the indenter. Although material ductility in heat affected zone can considerably change compared with base material, the present investigation is limited to fracture in base plate.

1.2. Limitations

The main motivation for the paper is to test the fidelity of existing FE simulation approaches for bridging the fracture ductility information from small coupon scale tests to large structural components. This relates to the concern for low velocity ship collision impacts. However, the investigation excludes the strain rate effect to the extent where effect can be observed on material behaviour and dynamic effects on the deformation mode. Such a quasi-static analysis method is often used and justified in engineering practice when the principal features of structural response under low velocity impact are well captured by the quasi-static method [21]. In the latter, it is demonstrated in that error of quasi-static analyses in beam impact problem reduces with increasing mass ratio between striking and struck object. Adopting the same principle to a 90-degree ship collision between two similar size ships, might suggest why most of the ship collision analysis neglects the dynamic effects, see e.g. [22]. For all the practical purposes, it is reasonable to approximate the mass of the striking ship much higher, since the mass of the struck ship can be approximated by the mass of the confined region between rigid bulkheads that is damaged during the collision event. Strain rate effects, on the other hand, are excluded because of the lack of robust method which formulates the combined effects of element length, stress triaxiality and strain rate on the ductile fracture strain under the plane stress shell element framework. Furthermore, it is generally agreed that in ship collision analysis inclusion of strain-rate effects is detrimental to simulation accuracy without careful calibration [23], and analysis excluding strain-rate effects are conservative as the estimated indentation into the struck vessel decreases with increasing strain-rate hardening that in turn leads to smaller opening size.