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Experimental and numerical analysis of laterally impacted stiffened plates considering the effect of strain rate

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ABSTRACT

A proper numerical simulation method is developed to simulate structure impact problems that consider the effect of strain rate. High-speed tensile tests were carried out to obtain the stress–strain relationships at different strain rates, and these results were used as material inputs to analyze the dynamic response of laterally impacted stiffened plates. The simulation results are compared with falling weight impact experiments, and good agreement was obtained. The stress–strain relationships obtained from high-speed tensile tests and the Cowper–Symonds constitutive (CS) model were compared. Part of the results shows that the curve obtained from the CS model is higher than that obtained from the high-speed tensile test and that with increasing strain rate, the distance will become more pronounced. The numerical simulation is verified and fits the experimental result well. The failure strain is affected by the mesh size in finite element simulation and will decrease with decreasing mesh size. Different mesh sizes for the model can be simulated accurately, once an appropriate material input is obtained. These conclusions can be very useful for studying large-scale impact problems, such as ship collisions and groundings, and can guide engineering applications.

1. Introduction

The basic structural elements of ships and offshore structures are stiffened plates. These elements are always exposed to dynamic loads, such as ship grounding, collision and impact from objects dropped on deck structures. Consequently, the design of marine structures requires accurate predictions of the extent of damage on stiffened plates subjected to an accidental impact, by incorporating the effect of permanent deformation and maximum force, as well as the stress and strain distribution.

Although many experimental studies have been performed to investigate stiffened plates or double structures under impact loading, most of this work has focused on examining the impact response by penetrating the panels using quasi-static lateral loads (Wang et al., 2000; Alsos and Amdahl, 2009; Paik and Pedersen, 1996; Paik and Seo, 2007). The quasi-static test is generally considered to have the advantage of continuous recording of the damage process, and thus, detailed information can be obtained from each specimen. However, a quasi-static test has the disadvantage of neglecting dynamic effects, which are produced by high-impact forces that occur upon indenter-structure contact during collision. As far as we know, dynamic effects have also been considered in both the experimental and numerical research studies to investigate the dynamic responses of small specimens under impact loads, and good agreement has been obtained between experimental and simulated results (Liu et al., 2013a, 2013b, 2014; Villavicencio et al., 2013; Villavicencio and Guedes Soares, 2011, 2012a, 2012b; Cho and Lee, 2009). All of these results provide better understanding of the dynamic response of structures. However, it is necessary to mention that the specimen and impact load used in these works were too small; the dynamic response of these small specimens will be affected by the boundary conditions.

Considering the costs and complexity of impact tests, especially large-scale structure-impact experiments such as collision and grounding, finite element analysis is considered a proper tool to predict the extent of damage in marine structural components (Pedersen, 2010; Villavicencio et al., 2014; Alsos et al., 2009). Certainly, the results obtained by the nonlinear dynamic analysis should be further validated with experimental tests before being implemented in structural design. In this respect, prior to performing analysis of large-scale structures, it is necessary to verify experimental-numerical models for large dynamic deformations

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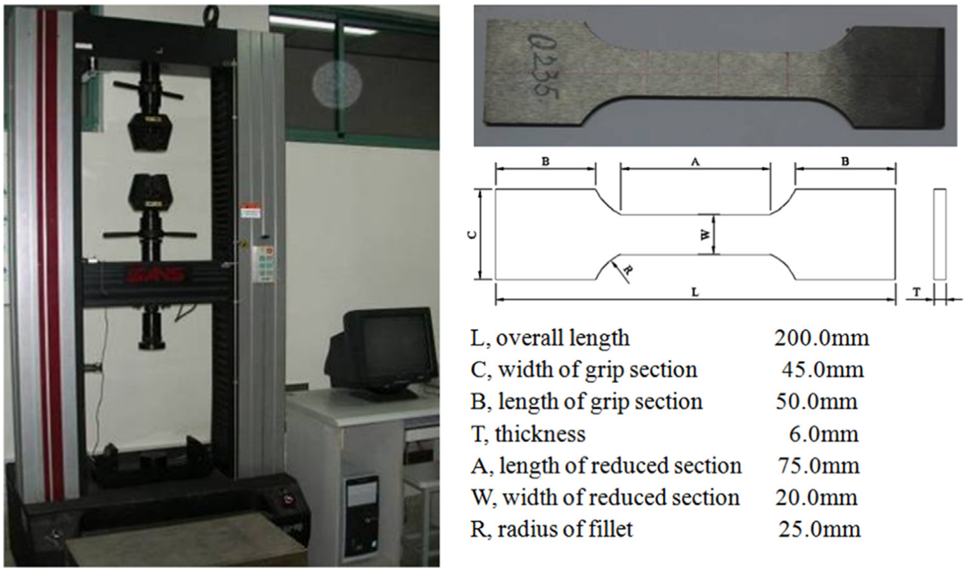
in local structural elements, which provides a basis for designing complex engineering structures that are subjected to dynamic impact loads.

Recently, Jones (2013) and Tanimura et al. (2014) have discussed some aspects of particular relevance to the behavior of structures subjected to dynamic, blast and impact loading that produce large inelastic strains, which might give rise to difficulties in interpreting numerical calculations. As reported by Jones et al., dynamic material characteristics, comparison of the material constitutive models, and selection of constants in constitutive models are considered to be important factors for performing dynamic simulation accurately. These conclusions are very useful for guiding field studies.

One of the most important finite element definitions is material nonlinearity. It is well known that plastic strain hardening, true failure strain and plastic strain rate sensitivity are essential for predicting the extent of damage in structures under impact loads. The definition of strain hardening can be described through two different expressions: (i) the real stress–strain relationship for the zone before the maximum load (Dieter, 1986) and (ii) a power-law relationship for the zone beyond necking (Zhang et al., 2004).

The failure strain controls the initiation of ductile fracture and greatly depends on the size of finite elements. As far as we know, not only is the dynamic failure strain in a dynamic response hard to obtain, but also the failure criterion for describing the inelastic strains of structures subjected to dynamic loads is unclear (Yu and Jones, 1997). Therefore, in a practical application, the numerical simulations of tensile tests have been conducted to predict the critical failure strain used in finite element models of punching and impact tests (Liu et al., 2013a,2013b, 2014; Villavicencio and Guedes Soares, 2012a, 2012b; Naar et al., 2002). Liu et al. (2013a, 2013b) presented a method for estimating dynamic critical failure strain using the Cowper–Symonds constitutive model (CS model) by means of the inverse of the CS equation. However, the static failure strain and certain strain rate have to be achieved before application of this method, and it is not a simple task. Actually, it is difficult to obtain the accurate dynamic failure strain, let alone the application in simulation. Meanwhile, for most studies



L, overall length	200.0mm
C, width of grip section	45.0mm
B, length of grip section	50.0mm
T, thickness	6.0mm
A, length of reduced section	75.0mm
W, width of reduced section	20.0mm
R, radius of fillet	25.0mm

Fig. 1. The quasi-static tensile test device and the standard dimensions of the test piece.

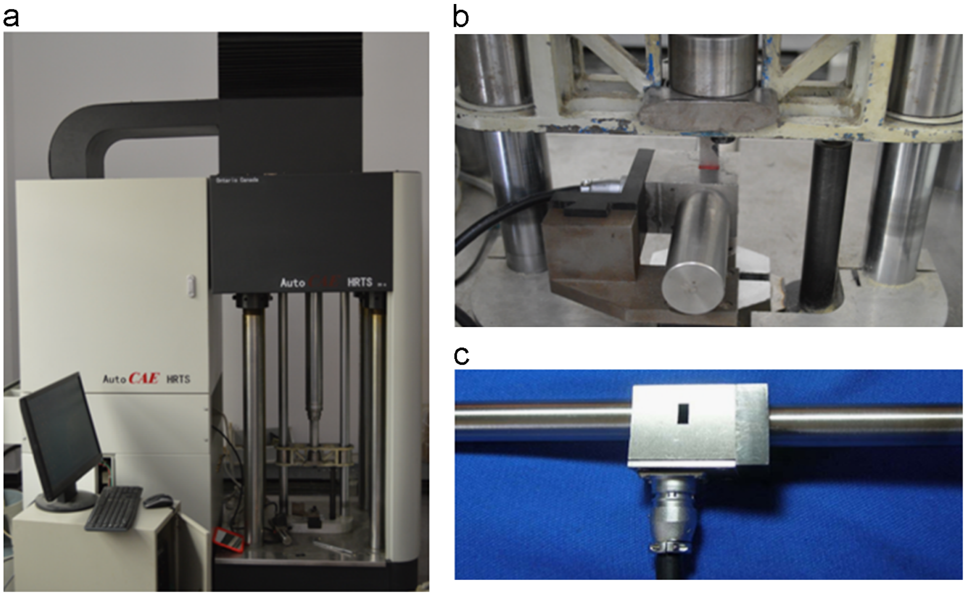


Fig. 2. Diagram of the high-speed tensile test instrument: (a) high-speed tensile test system, (b) specimen, extensometer and fixtures, (c) Poisson's ratio extensometer.