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Strain rate sensitive steel constitutive models for finite element analysis of vessel-structure impacts

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A B S T R A C T

Civil infrastructure systems such as bridge piers, navigational guide walls, and protection structures that are located near navigable waterways are inherently at risk for being impacted by cargo vessels such as barges and ships. To safely design such systems to possess adequate vessel impact resistance, structural loads associated with potential vessel-structure collision conditions must be quantified in a conservative manner. While high-resolution finite element impact simulations may be employed to compute such loads, care must be exercised in defining the material characteristics of the vessel if conservative structural design loads are to be obtained. Importantly, constitutive relationships assigned to steel components in the vessel model must be capable of accounting for strain rate sensitivities and large-scale plastic deformations.

In the present study, strain rate sensitive constitutive models were developed for two types of steel commonly utilized in marine construction in the United States—ASTM A36 and ASTM A1011. Tension tests were conducted over a wide range of strain rates (7.00×10^{-5} s^{-1} – 250 s^{-1}) spanning from quasi-static to intermediate and high rates that are typically associated with vessel-structure impact events. A novel testing apparatus—employing an impact pendulum as an energy supply mechanism—was designed for this study to conduct intermediate to high-rate

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material testing. Features of the apparatus, discussed in this paper, overcome key problems encountered in other studies that have employed impact loading for tensile material testing. From the testing program, representative stress–strain relations and Cowper–Symonds strain rate sensitivity parameters were developed for the materials tested. Rate sensitivities of the two steel grades tested were found to be very similar to each other. Additionally, rate sensitivities from the present study agreed well with ultimate stress data measured in past studies of mild steel, but were found to be less rate-sensitive than yield stress data measured in past studies.

1. Introduction

Vessel impact events can impart significant structural demands on exposed marine structures, with resulting response modes being highly dependent on the dynamic interactions between the vessel and components of the impacted structure. Consequently, to accurately and conservatively quantify vessel impact loads on marine structures, it is critical to have an adequate description of relevant dynamic phenomena, including inertial resistance mechanisms and rate-dependent material behavior in the impacting vessel. One of the most commonly employed techniques for quantifying vessel impact loads on structures is through finite element simulations, which offer a number of clear advantages in this area of investigation: 1) impact scenarios can be studied that would be unsafe or unreasonably costly to investigate experimentally; 2) parametric studies can uncover previously undetermined sensitivities to variable impact conditions; and 3) dynamic interaction between the vessel and impacted structure and the influence of such interaction on impact forces can be investigated in greater detail. In past studies, analytical tools have been used to predict vessel impact behavior for a variety of different structures common to marine environments, including bridge piers [1], offshore platforms [2], and fendering systems [3]. However, load predictions based on finite element analysis rely on accurate constitutive relationships to characterize material-level behavior at appropriate strain rates. In support of analytical efforts to quantify vessel impact loads on structures, the current study focused on the development of strain rate-dependent material models for two types of steel commonly employed in the United States: ASTM A36 steel—used in barge and bridge fender construction—and ASTM A1011 steel—used in the fabrication of sheet pile walls and bulkheads [4].

A viscoplastic constitutive model for A36 steel was employed in prior analytical studies of vessel impacts on structures [1,5–8] conducted using the LS-DYNA finite element analysis code. This constitutive model included both a representative A36 stress–strain relationship adopted from the literature [9], and strain-rate sensitivity as described by the Cowper–Symonds model:

$$\frac{\sigma_{\text{dyn}}}{\sigma_{\text{st}}} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P} \tag{1}$$

in which σ_{dyn} is the dynamic flow stress, and σ_{st} is the stress at a theoretical static state in which $\dot{\varepsilon} = 0$. Cowper–Symonds representation of material strain rate sensitivity is commonly employed in finite element impact simulations of steel marine structures [10,11], but requires appropriate selection of sensitivity parameters. In studies [1,5–8], Cowper–Symonds coefficients of $C = 40.4\ \text{s}^{-1}$ and $P = 5.00$ were employed, as is common practice for steel [12]. It is recognized, however, that the Cowper–Symonds parameters vary widely among different studies of mild steel [12–15]. Consequently, in the present study, uniaxial tension tests were conducted over a wide range of strain rates ($7.00 \times 10^{-5}\ \text{s}^{-1} - 250\ \text{s}^{-1}$) to characterize Cowper–Symonds coefficients (C and P) for A36 and A1011 plate specimens. A novel impact testing apparatus was designed for this study that employs a large-