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Nonlinear dynamic response of steel materials and plain plate systems to impact loads: Review and validation

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ABSTRACT

A finite element analysis (**FEA**) model to evaluate the nonlinear effects of severe dynamic loads on engineered structures requires an appropriate constitutive model of the structural material. Although some dynamic constitutive models for steels including mild and high strength steels are specified in offshore design guidelines, their limitations when applied to analysis of severe impact effects haven't been examined in any details. This paper demonstrates that the structural performance of a steel plate system subjected to impact load of a dropped object is highly sensitive to the adopted dynamic constitutive model using an existing experimental study. The stress-strain response of the plate is strongly dependent on the mechanical and geometrical properties of the steel specimen and the strain rate due to the impact load. While the dynamic constitutive model recommended by Det Norske Veritas (**DNV**) often overestimates or underestimates the structural response due to impact load, the proposed constitutive model leads to a significant improvement in the DNV recommendations.

1. Introduction

Despite anticipated risks to offshore installations due to harsh environmental and operational conditions, society traditionally has accepted such risks in return for the economic benefits from offshore energy resources. However, after the historic offshore disasters in the North Sea (i.e. the Piper Alpha Disaster of 1988) and in the Gulf of Mexico (i.e. Deepwater Horizon Disaster in 2010), which led to significant casualties and economic losses, as well as damage to the environment [1,2], the design and management paradigm for offshore structures has changed. A probabilistic risk-based design approach now is required by international rules and regulations [3–5] for offshore structures to assess the consequences of accidental actions such as ship collisions, dropped object impacts, fires, and explosions. This approach has been mandated because of the potential consequences of offshore accidents and increasing attention by regulators to the safety of offshore installations.

A structural risk, expressed in terms of probability or mean annual frequency (**MAF**), requires knowledge of the annual probability (or MAF) of occurrence for a specific hazard and the failure probability of a structural system given a structural load induced by the hazard parameters. While the occurrence probability depends on the quality of the recorded hazard data, a sophisticated structural analysis approach generally is required to predict the failure probability of the structural system. In addition, International Standards [4] stipulates that structural performance evaluation should account for nonlinear and dynamic effects of forces acting on offshore structures. Hence, the utilization of nonlinear transient finite element analysis (**NTFEA**) in structural engineering has been increasing in offshore platform design, concurrent to improvements in computational performance and growing concerns regarding safety [6–8].

Subtle changes in model parameters at the constitutive level are known to yield considerable changes in structural responses determined by NTFEA at the system level [9,10]. Hence, an adequate constitutive model for each structural material should be incorporated into the NTFEA model to improve the accuracy of the structural performance evaluation. Dynamic material responses at the constitutive level, including plastic flow stresses and strains, vary with the rate of change in strain over the time for structural steels. Fig. 1 shows such variations in true stress-strain responses at different strain rates obtained by laboratory tensile tests for two different mild steels ("True" stress-strain responses are utilized in LS-DYNA for NTFEA as input. Hence, plots are displayed in terms of true values for the stress-strain responses in this paper). Yield stress and ultimate stress typically increase as the strain rate increases while elastic moduli and failure strains remain almost constant with changing strain rates for both mild steels.

These dynamic material properties can be estimated by various laboratory experimental techniques. Although the early experimental

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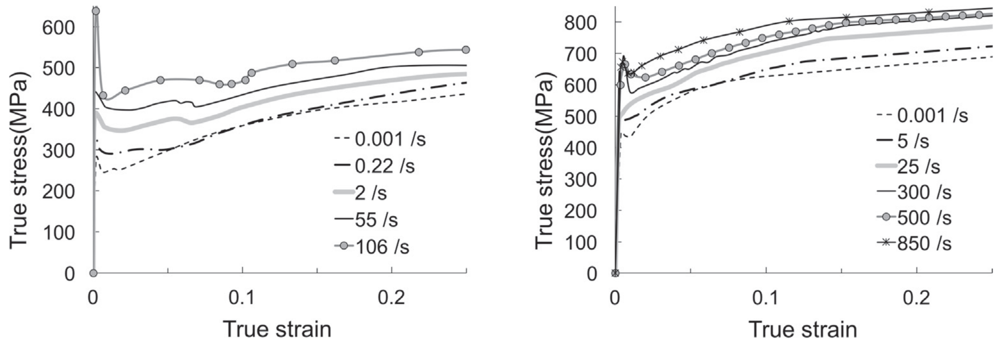

(a) Lower strength mild steel [13] *(b) Higher strength mild steel [14]*

Fig. 1. Experimental dynamic stress-strain curves at different strain rates for mild steels.

approaches were limited to low strain rates with classical dynamic compression tests using the split-Hopkinson pressure bar or Kolsky bar, new experimental approaches such as the dynamic tension and torsion test [11] and high strain-rate pressure-shear test [12] facilitate dynamic material tests at higher strain rates up to $10^6\,s^{-1}$. While mild steels were tested by Symonds in the late 1900s [13] at lower strain rates up to $106\,s^{-1}$ as shown in Fig. 1 (a), Forni et al. [14] recently provided experimental results for typical offshore structural steels at higher strain rates up to $850\,s^{-1}$ as shown in Fig. 1(b). Comparing these two-different mild steel test results indicates that changes in stress are less sensitive to strain-rate variations with high-strength steels (355 MPa) (Fig. 1(b)) compared to steels with lower yield strength (245 MPa) (Fig. 1(a)) [15].

Other researchers have tried to categorize different dynamic loadings such as creep loads, quasi static loads, earthquakes, impact loads, and blasts into strain rates. This relationship between strain rates and dynamic forces is important to determine appropriate dynamic material properties when to solve a specific dynamic problem for more reliable and robust NTFEA results. However, it is challenging to relate each loading type to a specific strain rate due to large variations in each loading type. In addition, this rate of change also varies for different structural materials. Two different categories proposed by Ngo et al. [16] and Goel [17] are not identical as displayed in Fig. 2. Since the assumptions and limitations of these proposed categorizations of different loading types into strain rates are not properly stated in these studies, it is hard to clarify the main factors causing the discrepancy between these two categories. Obviously, more experimental data obtained using more advanced experimental technologies for each type of loading and for each material are necessary to improve this load characterization.

Over the past two decades, many researchers have investigated the effects of strain rates for structural materials and have developed dynamic constitutive models. Two of these models, developed by Cowper and Symonds [18] and Johnson and Cook [19], have been widely adopted in the offshore industries. The Cowper and Symonds (**CS**) model has been utilized for design and evaluation guidelines for offshore structures [20]. However, only limited experimental data have been developed to identify the parameters of each model, which leads to large uncertainties in NTFEA results when they are used in structural performance assessment [21]. Moreover, there is no consistency in the CS model parameters for the same material suggested by different researchers [15], as noted subsequently. While the Norwegian classification society, Det Norske Veritas (**DNV**) has proposed specific values of the CS strain-rate effect parameters for common offshore steel materials [20], the effect of uncertainties in DNV's strain-rate effect parameters on the system-level structural performances has yet to be addressed.

Forni et al. [14] recently investigated the CS model and Johnson and Cook (**JC**) models for a specific offshore structural steel with the engineering yield strength of 355 MPa (S355) by experiments for a wide range of strain rates. They calibrated the strain-rate effect parameters for both CS and JC models to provide a better fit to the experimental curves and demonstrated that the JC model generally is more effective in fitting the experimental curves than the CS model. Their numerical validation, however, was limited to a lower strain range: 8% for strain-rate of $10^{-3}\,s^{-1}$ and 15% for strain-rate of $500\,s^{-1}$ although their experimental data present the failure strains reach up to 50% at higher strain rates.

The main objective of this study is to demonstrate the sensitivity of the nonlinear transient structural responses to constitutive models for different strain rates. First, existing dynamic constitutive models (i.e. CS and JC models) were examined for different strain rates using larger tensile plastic strains up to 30%. For this constitutive model validation, Forni et al.'s experimental results in Fig. 1(b) were employed. Secondly, NTFEA was carried out for a steel plate system subjected to different dropped object impact loads using LS-DYNA, to elucidate the significance of the choice of constitutive model on the structural performance evaluation at the system level. A typical grade mild steel in the offshore field is used for this study such as the Grade S355 and ST53-3N in the Euro Code and German DNI respectively with equivalent static mechanical properties.

2. Dynamic constitutive models

Attempts has been made to integrate the nonlinear and dynamic feature of material behavior to the finite element analysis platforms by utilizing both Johnson and Cook (**JC**) and Cowper-Symonds (**CS**) models to improve structural performance evaluation. In-depth understanding of the characteristics of these dynamic constitutive models is necessary to interpret the effect of variations in the model parameters for the same strain rate-dependent material due to limited materials tested and lack of consensus on model parameters in the literature. Existing data on the model parameters and material properties for the available tested steel materials were thoroughly tracked and are presented in this paper for both constitutive models.

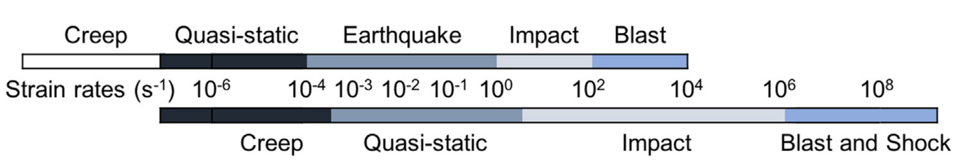

Fig. 2. Strain-rate range for different loading types suggested by different researchers: Ngo et al. [16] (**top** figure) and Goel [17] (**bottom** figure).