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A damage-based failure model for coarsely meshed shell structures

Martin Storheim [a, b, c, *], Hagbart S. Alsos [d], Odd Sture Hopperstad [e], Jørgen Amdahl [a, b, c]

[a] Norwegian University of Science and Technology, Institute of Marine Technology, NO-7491 Trondheim, Norway
[b] Centre for Sustainable Arctic Marine and Coastal Technology (SAMCoT), Norway
[c] Centre for Autonomous Marine Operations and Systems (AMOS), Norway
[d] Reinertsen AS, Trondheim, Norway
[e] Structural Impact Laboratory (SIMLab), Center for Research-based Innovation, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

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A B S T R A C T

This paper presents a fast and reliable method for failure prediction of coarsely meshed shell structures. The method is especially relevant when investigating the impact performance of offshore structures, typically stiffened panel structures where the size of the structure limits the possible detailing level during analysis.

The method combines a local instability criterion with post-necking damage in order to numerically model the failure process in large shell elements. The failure model is based on power law plasticity with the stress-based Bressan–Williams–Hill (BWH) local instability criterion and a coupled damage model after incipient necking. The BWH criterion gives a robust estimation of incipient necking for coarsely meshed shell structures. After necking starts, a mesh-size dependent damage model is coupled to the element strength for material softening until failure, assuming that the strain localization occurs locally inside the element within a virtual neck. The model is incorporated in the explicit FE code LS-DYNA.

The material model formulation is validated against experiments at several levels; from formability tests with varying strain states to medium and large scale impact experiments, giving a robust prediction of energy dissipation and material failure in the structure with low mesh dependency.

The material model is calibrated from a single uniaxial test, and gives robust and consistent simulation results in which details of the localized necking phenomenon is included in the behavior of large shell elements. Thus, it is readily used for structural design of offshore structures in order to assess the technical safety level of the structure against collisions in all phases of the design process.

1. Introduction

The consequences of a ship collision event can be severe, varying from local deformations to large-scale fracture with potential environmental pollution due to rupture of cargo tanks or complete loss of the ship and crew. There is a need for a robust method to assess the consequences of a ship collision in the design phase of typical offshore installations. No consensus has been reached for how the industry should conduct such analysis, as there is no readily available robust method for assessing fracture in coarsely meshed stiffened panel structures. A designer is thus left with the challenge of either conducting a large experimental test program or to make conservative assumptions in order to document the structural resistance to and the damage extent from a typical collision event.

A typical offshore structure can have a multitude of material types and qualities, whose plastic properties can have a wide scatter. This necessitates a material representation that is easily calibrated towards simple material tests or standard material grades for ships and offshore use, in order to enable engineers to assess the crashworthiness of marine structures in a reliable manner.

Prototype testing is limited to scale models due to the size and cost of the structures involved. This implies that material failure must be calibrated in a domain outside of the structural application domain, and the response should transfer from the smaller calibration scale to the larger structural scale.

* Corresponding author. Norwegian University of Science and Technology, Institute of Marine Technology, NO-7491 Trondheim, Norway. Tel.: +47 73 59 57 10.
E-mail address: martin.storheim@ntnu.no (M. Storheim).

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A real collision event will differ substantially from a design collision event with respect to the shape and structural layout of the striking ship, the impact location, velocity and material strength. Further, the fabrication tolerances for a ship structure are generous. Due to the sum of uncertainties, the acceptable accuracy for fracture prediction in a ship collision simulation is large. Typically, a 10–15% uncertainty of the peak force prior to side shell fracture may be regarded as acceptable, with the uncertainty rather resulting in premature fracture than an overly optimistic response. A good representation of the energy dissipation vs. indentation is important.

The proposed model in this paper attempts to fulfill these needs. To validate the model, both material testing and scaled impact experiments of typical ship and offshore structures are simulated and compared.

2. Background

Material behavior in large-scale collision assessment and sheet metal forming is similar, with thin plates subjected to large in-plane and out-of-plane deformation. As the plates are thin, plane-stress conditions apply. After significant plastic strains, a diffuse or local neck will start to develop. Diffuse necking is defined as a state with contraction strains in both the width and the thickness direction of the structural component, whereas local necking has a length scale similar to the plate thickness and occurs under vanishing strain along the neck. Thus, local necking takes place under plane-strain conditions, as reported by Refs. [1,2].

Within the local neck, the failure mechanisms are shear fracture due to shear band localization and ductile fracture due to nucleation, growth and coalescence of voids. A very detailed mesh is needed in order to capture these effects properly in a finite element model of a structural component, typically only possible with solid elements. As the local necking instability has a width in the range of the plate thickness, shell elements with length equal to thickness should capture most of the local necking phenomenon provided a good element formulation is used. In this context, it can thus be described as a very refined mesh.

Due to the large dimensions of the colliding ship structures, computational limitations dictate the minimum mesh size permissible for finite element analysis. On the other hand, the maximum mesh size is governed by the capability of the chosen element formulation to precisely capture the plate buckling and plastic behavior. The mesh sizes typically used for such analyses are in the range of five to ten times the plate thickness, giving a minimum of three elements over the stiffener web height and five to six elements in the plate between each stiffener. Depending on the structure, these mesh sizes may be refined enough to track strain localization in the form of diffuse necking. However, out-of-plane strain concentrations close to stiffening members are normally not captured, and it is thus considered a coarse mesh. Larger element sizes than ten times the plate thickness are typically not recommended for the application of ship collisions, but may be permissible in other circumstances.

A typical engineering approach to account for fracture is to define a critical fracture strain, which can be estimated from material testing. The method is easily applied in finite element codes, but poses some limitations on the accuracy of the obtained results. Aretz [3] points out that necking occurs at a critical equivalent plastic strain, but the critical strain will be a function of the applied strain mode. Bai and Wierzbicki [4] show that the plane stress critical strain reaches a maximum for compression, uniaxial tension and bi-axial tension, whereas minimum critical strains are found for pure shear and plane strain. Thus, using a material model with critical plastic strain obtained from uniaxial testing may be non-conservative.

Alsos et al. [5] and Aretz [6] summarize different methods for assessing fracture in sheet metal forming applications. The Keeler–Goodwin approach [7,8] has been a dominating method, in which a forming limit diagram (FLD) is created by plotting the principal strains ε_1 and ε_2 at the onset of plastic instability. This method assumes proportional strain paths, i.e. that the ratio β between the minor principal strain rate $\dot{\varepsilon}_2$ and the major principal strain rate $\dot{\varepsilon}_1$

$$\beta = \frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} \quad (1)$$

remains constant during the deformation. However, this is not necessarily the case for large plastic deformations due to non-linearities from strain hardening, geometrical changes and contact between different structural components.

Strain-based FLDs can be constructed from a range of material tests at different strain states. Analytically, the forming limit curve (FLC) in the FLDs can be constructed from different proposed theories, e.g. Hill [1], Bressan and Williams [9] and Marciniak and Kuczynski (M–K) [10].

A simple alternative to the strain-based FLD is the stress-based FLD as proposed by Stoughton [11], assuming that the stress-based criterion is less affected by changing strain paths. Yoshida et al. [12] investigated the strain-path dependence based on M–K analysis, and found that the stress-based FLDs are not independent of the stress-path if abrupt changes in the path are imposed without unloading.

For coarsely meshed shell structures, Alsos et al. [5] proposed the stress-based BWH instability criterion combining the Bressan–Williams [9] and Hill [1] necking criteria. This criterion is easy to implement numerically. Alsos et al. demonstrated that numerical simulations with this criterion gave good agreement with experimental data, which was later supported by the findings of Paul [13]. The BWH criterion assumes no initial defects. A strong argument for the criterion is that it can be calibrated from the power law hardening parameters, and can thus be used without an extensive test program for regular structural steel with low anisotropy.

The BWH instability criterion can be scaled to predict the same initiation point of local necking with low mesh dependency. However, element removal when the BWH instability criterion is reached will underestimate the failure strain as the post-necking strain is not included, as pointed out by among others Hogström and Ringsberg [14]. If the analysis is continued in the post-necking region without element erosion, the results diverge with varying element size.

The post-necking energy dissipation in each element may be small. However, for a complex structure with large deformations, the additional resistance in the post-necking behavior of the element may significantly increase the plastic dissipation in the surrounding structure, thereby giving a significant total contribution to the energy dissipation. Thus, it is important to erode the element as closely as possible to the real occurrence of fracture in order to avoid too rapid fracture propagation.

Aretz et al. [15] recently proposed a novel approach to include post-necking and ductile fracture behavior in aluminum sheets during forming processes. Motivated by the dominating role of tensile loading in the necking and fracture process, a loading parameter α was defined to assess the degree of tensile loading. With this parameter, a new equivalent plastic tensile strain ε_t can be defined. Using a modified Freudenthal criterion, depending among other factors on the parameter α and the mesh size, the critical fracture strain can be found. This proposed model is promising, but requires significant experimental testing in order to be calibrated.