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Non-linear effective properties for web-core steel sandwich panels in tension

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ABSTRACT

All-metal sandwich panels with a low weight-to-stiffness ratio provide the means to develop cost and energy efficient large-scale thin-walled structures such as ships. However, the modeling and computational effort for a three-dimensional (3-D) sandwich structures may be significant especially in the limit state analysis of ship structures. This can become a significant drawback especially in the conceptual design stage. To this end, we determine the load–displacement curves until tensile instability for orthotropic web-core sandwich panels under multi-axial tension loading. Load–displacement curves are determined by dividing sandwich panel into discrete members and analyzing each of the constituents separately. Combined response is obtained by rule of mixtures. Tensile instability of panel is assessed using analytical necking criteria. Validity of the analytically obtained curves is established by comparing them with those obtained by a 3-D Finite Element Modeling (FEM) of the unit cell. Analyses with the unit cells show that while stiffness of the orthotropic sandwich panels is strongly direction dependent, tensile instability of panels is direction independent and governed by the faceplates. The analytical curves are then implemented to ABAQUS UGENS subroutine to describe the non-linear mechanical shell section behavior in the framework of Equivalent Single Layer (ESL) theory. The subroutine was used to simulate the response of idealized accommodation deck, with and without of a cut-out, of a passenger ship. Good agreement in response was found between 3-D FEM and ESL.

1. Introduction

Sandwich panels are three-layered structures that consist of two face sheets separated by the core. Incentive to develop light and strong constructions have placed sandwich panels in an excellent position compared with stiffened or isotropic plates since they can offer significant weight savings at equal strength [1]. This has sparked an interest in marine, civil, automotive and aviation industries to exploit the benefits of sandwich panels in design of cost and weight efficient structures; see [2–9] and Noor et al. [10] for generic overview of sandwich panels. Steel sandwich panels have been also proposed for ship hulls to be used in decks and double-hulls as well as in side structures for impact mitigation [4,11–15]. However, FE modeling and analysis of such structures numerically becomes prohibitive considering the level of details (face and core) that must be represented with the sufficiently fine mesh. Fine mesh is needed to reliably simulate different failure mechanisms such as folding and crushing (see for example Paik [16]) and potential ductile failure in these constituents.

Therefore, the analysis of sandwich panels during the design process is often performed in terms of linear elastic effective mechanical properties rather than by means of direct computational model [10,17]. Essentially this means that the sandwich panel is replaced with the conventional plate using the effective in-plane, bending and coupling stiffness; in case of significant out-of-plane shear deformation also the shear stiffness has central role in response prediction. Libove and Batdorf [18] and Libove and Hubka [19] were the first ones to propose Equivalent Single Layer (ESL) theory for corrugated core sandwich panels. Since then several investigations have been carried out on ESL approach representing steel sandwich panels as reviewed in [3,20]. For linear elastic response important issue is the homogenization-localization scheme that defines the first fiber yield, which is often used as a design criterion in structural analysis [20,21]. This criterion should be used in optimization. Optimization of the plates for lateral loads is performed in [3,6,22] using ESL. However, these investigations lack the plate buckling and ultimate strength criterion. Recent investigations have been developing ESL approach in this direction [23–26]. Nevertheless, as part of the large structures, such as ship hull-girders or steel bridges, the panels can be simultaneously exposed to large in-plane tension loads. Therefore, there is a clear need to investigate how to embed material non-

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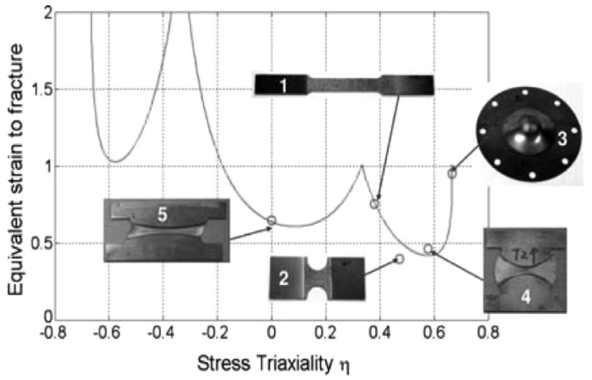

Fig. 1. Fracture initiation strain as a function of stress triaxiality $\eta = \sigma_m/\sigma_e$ (mean stress divided by equivalent stress) – plane stress fracture locus for Al2024-T351. Figure from [31].

linearity into ESL approach so that large plastic deformations and consequent plastic instability (including softening and fracture) under tension dominated loading could be simulated without the detailed FE mesh. Present investigation aims to fill this gap, as only then we can develop truly versatile ESL approach capable of handling both, compressive and tensions loads, respectively.

Herein, we consider the behavior of panels until plastic instability that is a precursor to ductile fracture. Fracture ductility shows the material ability to go through significant plastic deformation before fracture. For isotropic material ductile fracture is a local phenomenon that depends on the stress state in the material, see Fig. 1. This relation needs to be properly *upscaled* in order to predict failure in realistic, large-scale structural models, where the shell elements are employed for their computational efficiency over detailed solid mesh. Herein, *upscaling* is defined as moving from one homogenous continuum scale to another, without consideration of heterogeneity of the microstructure. Different upscaling methods have been presented recently applicable to isotropic plates [27–30]. However, to the best of authors' knowledge, there is no upscaling method available to predict plastic instability and consequent ductile failure in homogenized orthotropic sandwich panels, where orthotropy is induced by interaction of sandwich constituents while the sandwich panel itself is represented as a single ESL element.

Therefore, the aim of the present paper is to analyze the behavior of orthotropic web-core steel sandwich panels under multi-axial tension, and thus extend the versatility of the ESL approach by considering tensile loads. On the one hand, the present investigation contributes to the understanding of how stress state dependent plastic instability upscales from isotropic plate to orthotropic panel level, assuming that orthotropy is caused by the geometry of the panel while materials of the constituents are isotropic. On the other hand, the study provides a first step towards a computationally efficient method for accidental limit state prediction with FE method under multi-axial tensile loads. Therefore, the response of orthotropic web-core steel sandwich panel under tension is analyzed until tensile instability. One of the principal, strongly counterintuitive findings is that despite of the orthotropic nature of the web-core sandwich panel, the onset of tensile instability in the panel is independent of the loading direction while the load–displacement curve depends considerably on the loading direction. Tensile instability is direction independent because failure occurs in the faceplates of the sandwich, thus from the instability point of view orthotropic web core sandwich panel can be considered as isotropic panel. In other words, the direction independence arises due to the discrete and orthotropic nature of web-core sandwich panels, which is why the results cannot be generalized for other type of sandwich structures. Furthermore, for accurate analytical prediction of the point of instability we emphasize the selection of correct instability mode (localized vs. diffuse necking) under different global boundary constraints.

2. Panel geometry and boundary conditions

The web-core orthotropic sandwich panel analyzed in this study is shown Fig. 2(A). The periodic nature of the web-core panel makes it possible to focus the analysis on a single repetitive unit cell shown in Fig. 2(B). Geometry of the unit cell is defined by the lengths in two principal directions L_1 and L_2, panel height of h, face sheets of equal thickness t_F and web thickness of t_W, whereas in the present investigation we assume that $t_F < t_W$. The unit cell is deformed under two different type of *global* boundary constraints identified by the stress state they induce in the unit cell: PST – plane strain tension, and UAT – uniaxial tension; see Fig. 2(C). These explicitly defined constraints are termed *global* to distinguish them from local constraints (stress states) arising in the constituents: faces and web, of the unit cell. Because of the

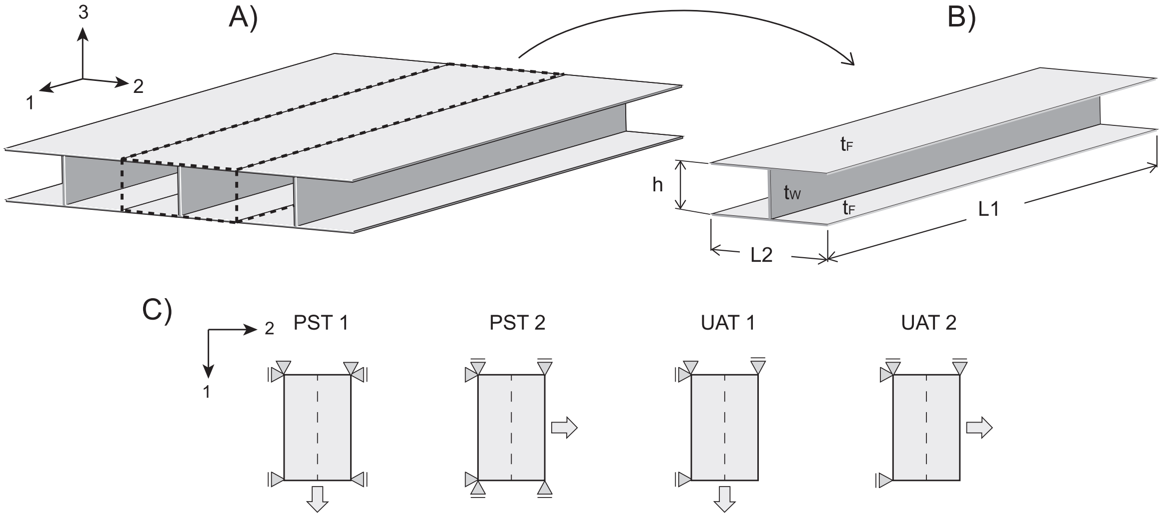

Fig. 2. A) Web-core sandwich panel and B) unit cell of the analyzed web-core sandwich panel. C) loading modes considered in this study (PST – plane strain tension; UAT – uniaxial tension).

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