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High velocity compressive response of metallic corrugated core sandwich columns

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ABSTRACT

The high velocity compressive response of metallic corrugated core sandwich columns was characterized. One end of a column was compressed, either perpendicular-to-corrugations or parallel-to-corrugations, at a uniform velocity up to 100 m/s whereas the other end was held fixed. Numerical simulations revealed that the response differs from the low velocity response dominated by inertial stabilization; the perpendicular-to-corrugations compressive response was characterized by repetitive densification in a unit cell while the parallel-to-corrugations one occurred during one-way trip of stress wave. The effects of geometric imperfections, column length, compression velocity were investigated through the analysis on rate independent Al6061-T6 corrugated core sandwich columns. On the other hand, the influence of material strain-rate sensitivity was numerically assessed for SS304 corrugated core sandwich columns. As a result, the front end reaction forces increased with imposed velocity while the peak reaction forces on the back end remained invariant. No significant effect of geometric imperfections was observed, and the column length effect was associated with the time scale: the arrival time of stress wave and reaction force variation. Consequently, the analytical expressions for the response were given in terms of sandwich geometric dimensions and loading intensity.

1. Introduction

Metallic core sandwich structures have been recognized as promising structural elements protecting from high intensity dynamic loading. The benefits come from the distinctive attributes in sandwich constructions; distributed mass in the sandwich design considerably reduces momentum transferred from external environments, and proper selection of cores or incorporation of energy dissipating media in empty core sections absorbs the kinetic energy of flying objects [1,2]. Recent investigations on the mechanical response of the sandwich structures when exposed to various types of intense loading extend their potential applicability toward ship hull design against underwater blast [3–5], crashworthiness design [6,7], vehicular armor systems against soil blast [8,9], and ballistic impact mitigation structures [10–13].

The metallic core sandwich structures can also be subject to dynamic in-plane loading. For example, if employed for decks or bulkheads in a ship design, the structures may possibly be exposed to in-plane or oblique impacts. Recently, the authors discussed the response and dynamic effects of corrugated core sandwich columns under in-plane loading [14–16]. In the loading rate considered in those studies, the response is mainly dominated by lateral inertia and material strain-rate dependence, and quite sensitive to geometric curvature imperfections. However, there is a lack of information on the dynamic in-plane response of the metallic core sandwich structures if higher-intensity loading greater than 20 m/s is applied.

There are several investigations on the response of metallic core sandwich structures at the compression rate of loading rate ranging up to a few of hundred m/s, which front faces of typical sandwich panels can attain during an underwater blast [17]. However, their main focuses are on the out-of-plane compression of core. St-Pierre et al.[18] investigated the dynamic indentation response of panels with a corrugated or Y-frame core. From their numerical study, the response has been explored by increasing the imposed velocity up to 100 m/s for consideration of the structural elements into hull structures or land vehicles against blast loading or collision. In the basic study done by Ferri et al. [19], fundamental understanding on the high velocity dynamic response was gained through investigating the dynamic crushing response of I-core. In addition, Tilbrook [20] and Lee [21] independently investigated the dynamic out-of-plane response of corrugated core and

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Nomenclature

Superscript

(0), (1),.., (k)	material regions
(back)	back end
(front)	front end
(SW)	corrugated core sandwich column
(perp)	perpendicular-to-corrugations
(para)	parallel-to-corrugations

Subscript

(el)	elastic
(pl)	plastic
(fw)	face wrinkling mode
(g)	global buckling mode
ν	Poisson's ratio
ν_P	plastic Poisson's ratio (here, ν_P=0.5)
ω	corrugation angle
$\overline{\rho}$	core relative density
ρ	parent material density
σ_Y^0	quasi-static yield strength
$\sigma_Y(\dot{p})$	dynamic yield strength
σ_{eq}	equivalent stress
ε_Y'	yield strain in plane strain condition
ξ	the imperfection amplitude of global curvature
c	core height
$c_{(\cdot)}^{(\cdot)}$	elastic or elastic–plastic wave speed of columns such as corrugated core sandwich columns compressed perpendicular-to-corrugations or parallel-to-corrugations
D	material constant
E	Young's modulus
E_P	plastic modulus
E_T	tangent modulus
E_T'	the tangent modulus in plane strain condition
E^*	effective in-plane core stiffness
h	face sheet thickness
L	column span length
l	core ligament length
m	material constant
P_Y	in-plane load associated with yield stress
P	equivalent plastic strain
$\dot{p}$	equivalent plastic strain rate
R	the dynamic yield strength enhancement ratio
t	core ligament thickness, or time
$\Delta t_{(\cdot)}^{(\cdot)}$	the arrival time of elastic or plastic stress wave from the front end to the back end of sandwich column
V	compression velocity, rate-of-compression

of pyramidal core, respectively. On the other hand, collapse response of constituent inclined core plates was analyzed depending on the compression velocities: (1) inertial-stabilization dominating velocity regime; (2) buckle wave dominating velocity regime; (3) axial-plastic-shock-wave dominating velocity regime [22]. Vaughn et al. [23] presented the buckling wave phenomena when the constituent elements of pyramidal cores are subject to imposed compression velocities on the order of 100 m/s. However, there is little known about the dynamic in-plane response of sandwich columns at this range of loading rates.

In this study, the dynamic response of corrugated core sandwich columns under high velocities is numerically explored via FEM to gain insight on the dynamic in-plane response. In particular, the effects of applied velocity and sandwich column geometric dimensions on reaction force are noted. The investigation is mainly focused on the slender sandwich columns made of a rate-independent material, Al6061-T6, whose material strain-rate dependence can be neglected. Also, the effect of material strain-rate dependence on the dynamic response is analyzed through FE simulations on SS304 corrugated core sandwich columns by comparing two kinds of FE simulations, with and without consideration of the strain-rate sensitivity of the parent material.

The paper is organized as follows: In Section 2, details of the FE model are described. In Sections 3.1 and 3.2, the high velocity responses for corrugated core sandwich columns compressed perpendicular-to-corrugations and parallel-to-corrugations are investigated, respectively. Finally, simple analytic equations describing the observations are suggested in Section 3.3.

2. Numerical methods

2.1. Specimens and loadings

Consider a corrugated core sandwich column subject to dynamic in-plane loading as shown in Fig. 1. One end of sandwich column (front end) is compressed by a rigid plate at a constant rate of the order of tens of m/s (up to 100 m/s) while the other end (back end) is completely fixed. To find the distinction with respect to the loading directions, two in-plane loading directions, *perpendicular-to-corrugations* and *parallel-to-corrugations,* were considered independently as described in Fig. 1(a) and (b).

Two kinds of sandwich columns were considered depending on their parent materials: Al6061-T6 columns and SS304 columns. The geometry of sandwich columns is characterized by face sheet thickness, h, the length of corrugation leg, l, core height, c, core angle, ω, column length, L, as indicated in Fig. 1(c). Core relative density, $\overline{\rho}$, which defines the volume fraction occupied by materials in the core section, is given by

$$\overline{\rho}_{Al} = \frac{t/\sin\,\omega}{\ell\,\cos\,\omega + t/\sin\,\omega} \tag{1}$$

$$\overline{\rho}_{SS304} = \frac{2t}{\ell\,\sin\,2\omega} \tag{2}$$

Taking the general manufacturing range into consideration, the core relative densities in this study were selected from the previous investigations, 25% and 12% for Al6061T6 and SS304 corrugated core sandwich columns, respectively [13,24]. However, the responses are explored for various geometries by increasing L and h with core relative densities fixed. Our main focuses are on the slender columns whose non-dimensional ratio, L/c, is greater than 40. Column geometries and loading conditions for this investigation are summarized in Table 1.

2.2. FEA

A commercial FE package, ABAQUS/Explicit, is employed for the FE simulations. In-plane compression velocities, V, in the range of 20–100 m/s are imposed at one end of sandwich columns such that

$$V\Big/\left(c_{el}^{(SW)}\varepsilon_Y\right) > 1 \tag{3}$$

with a longitudinal wave speed of a sandwich column, $c_{el}^{(SW)}$, and yield strain, $\varepsilon_Y = \sigma_Y/E$. Depending on the in-plane loading