Engineering Structures 97 (2015) 80–89

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Quasi-static response of sandwich steel beams with corrugated cores

Sushrut Vaidya [a], Linhui Zhang [a], Dharma Maddala [b], Rainer Hebert [b], Jefferson T. Wright [c], Arun Shukla [c], Jeong-Ho Kim [a,*]

[a] Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Rd., U-3037, Storrs, CT 06269, USA
[b] Department of Chemical, Materials and Biomolecular Engineering, University of Connecticut, 97 N. Eagleville Road, Storrs, CT 06269, USA
[c] Dynamic Photomechanics Laboratory, Department of Mechanical Engineering and Applied Mechanics, University of Rhode Island, Kingston, RI 02881, USA

ARTICLE INFO

Article history:
Received 23 June 2014
Revised 26 January 2015
Accepted 3 April 2015
Available online 19 April 2015

Keywords:
Sandwich beam
Corrugated core
Graded core
Quasi-static loading
Three-point bending test
Finite element simulation

ABSTRACT

The response of sandwich steel beams with corrugated cores to quasi-static loading is investigated by employing experimental and computational approaches. The sandwich steel beam consists of top and bottom substrates made of AISI Steel 1018 and four corrugated core layers made of AISI Steel 1008. Various arrangements of the corrugated core layers with both uniform and graded layer thicknesses are considered. Three core arrangements with identical relative densities are used to study the effects of uniform versus graded core layer thicknesses onto the quasi-static behavior of corrugated steel beams. Finite element models are validated against quasi-static tests, and lender themselves suitable for a parametric study. A parametric study is also carried out on large-scale structural size beams of a few meters in length. The deformation modes observed in this study include core crushing, and plate bending and shear. It is found that core arrangement and beam span is key factors governing the quasi-static response of sandwich beams with corrugated cores.

1. Introduction

Structural systems such as building frames, bridges, cranes, ship hulls, and airframes are used in infrastructure, industrial, and transportation applications. These systems are usually constructed in the form of assemblies of structural components or members, which are subjected to various types of loads such as dead, live, wind, impact, and blast loads. The behavior of a structure varies with the type of load acting on it, depending on the characteristics of the load as well as the nature of the structure. It is common practice to distinguish between phenomena involving static and dynamic loading. The response of a structure to dynamic loading is time-dependent, and is characterized by the existence of inertia forces. In addition, material properties are usually strain rate-dependent, which may add to the complexity of structural response to dynamic loading. However, if the structure is gradually loaded, so that no inertia forces appear during the response of the structure, the problem may be considered static in nature. In order to obtain a complete picture of structural behavior, it is important to investigate the response of a particular structural system to both static and dynamic loading. In this paper, we use the term 'quasi-static loading' to refer to loading that is applied at a rate low enough to prevent the appearance of inertia forces, yet sufficiently high to allow experimental testing to be performed in a reasonable amount of time.

In recent times, it has become necessary to consider loads imposed by blasts and explosions in the design of civil infrastructure systems [1,2]. Blast loads pose multiple threats – such as blast waves and shrapnel – which can cause extreme damage to the structure. Structural design strategies for limiting the damage caused by a blast or explosion include the following: provision of structural continuity and redundancy in load paths, enhancement of the structure's capacity for energy absorption, and provision of reserve structural strength [2]. Researchers have investigated concepts such as sandwich structures [3], metal foams [4], and polymers [5], which can act as shock absorption devices to protect the primary structure. Due to the potentially superior performance of sandwich structures compared to monolithic structures under blast loading [6], significant research efforts have been devoted to the investigation of the behavior of sandwich structures under dynamic loads. The effects of different types of cores, such as trapezoidal, corrugated, honeycomb, tetrahedral, and pyramidal cores, on the blast resistance of sandwich structures, has been extensively studied in the literature [7–25]. To name a few, Xue and Hutchinson [9] demonstrated that sandwich beams outperform monolithic beams of the same material and the same total mass when subjected to blast. Fleck and Deshpande [10] used a three-phase model for sandwich plates: the fluid structure interaction phase; core compression phase; and plate bending and longitudinal stretching phase. They

* Corresponding author.
E-mail address: jhkim@engr.uconn.edu (J.-H. Kim).

http://dx.doi.org/10.1016/j.engstruct.2015.04.009

showed that the last two phases can be coupled. Tilbrook et al. [13] and Liang et al. [14] found that the soft core with a low transverse strength reduces the transmitted impulse during the fluid–structure interaction stage for water blast and increases the coupling between core compression and plate bending, but the soft core can be fully crushed and gives a very high support reaction. Avila [24] studied the behavior of sandwich beams with a functionally graded core, and proposed a failure mode criterion for such beams. Wang et al. [25] studied the dynamic behavior of sandwich panels with E-glass vinyl ester composite face sheets and a stepwise graded foam core under shock loading. They found that monotonically increasing the impedance of the foam core from the front of the structure (i.e. the region facing the shock loading) to the back can greatly enhance the dynamic performance of sandwich composites. Both quasi-static and dynamic response of corrugated core sandwich beams have been also investigated [26–29].

Zhang et al. [30] have recently investigated the dynamic response of steel sandwich structures with uniform and graded corrugated cores subject to shock tube induced dynamic air pressure and demonstrated that the beam corrugated with smoothly graded core layers outperform those with uniform and non-smoothly graded cores. The main motivation and contribution of this paper is to provide the effects of internal core arrangements into the quasi-static behavior, such as initial crushing load and load-deformation history, of corrugated steel beams. The present study also complements the work by Zhang et al. [30] by providing the quasi-static response of steel sandwich beams with corrugated cores.

There are significant qualitative and quantitative differences between the response of a structure to blast loading and its response to quasi-static loading. Consideration of the response of a structural system to quasi-static loads is an equally essential part of the complete structural design process. A critical evaluation of the quasi-static performance of sandwich beams with corrugated cores is necessary to achieve a complete understanding of the structural response of such systems. To address this gap, the quasi-static response of sandwich beams with uniform and graded corrugated cores is investigated by performing quasi-static tests on laboratory-scale specimens, and extending finite element simulations to large-scale beam specimens. Several core arrangements with uniform and graded core layer thicknesses are studied. Three of these arrangements have identical relative core densities. Also, the influence of layer arrangement on the quasi-static response and energy absorption capacity of corrugated core sandwich beams is extensively investigated.

Sandwich beams considered in this paper are envisioned as protective elements which are attached to the primary members of a structure, e.g. the beams and columns of a building frame. It is important to note that the specimens tested in this study are laboratory-scale models but finite element study is extended to

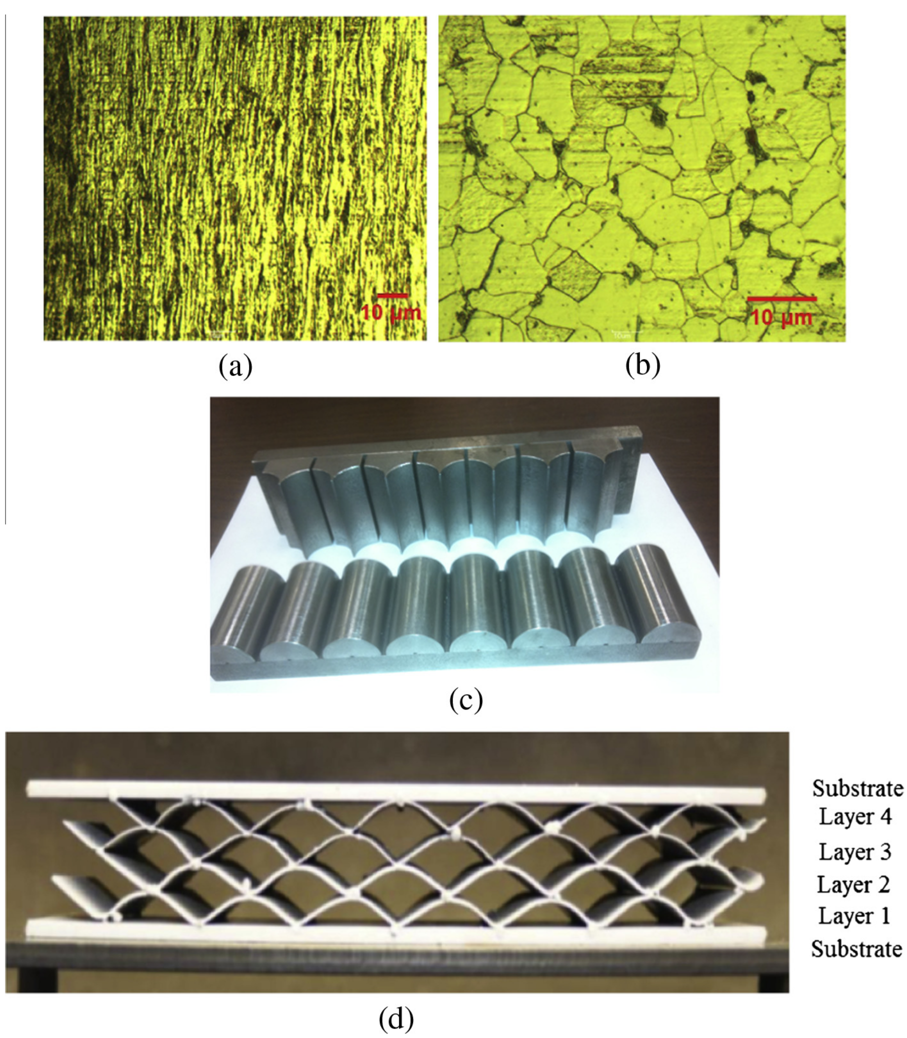

Fig. 1. (a) Microstructure of Steel 1008 as received; (b) microstructure of Steel 1008 after heating and cooling; (c) die used for corrugation; (d) assembled sandwich beam with four layers.