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Multi-objective optimization of laser-welded steel sandwich panels for static loads using a genetic algorithm

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ABSTRACT

We present a methodology for the multi-objective optimization of steel sandwich panels for prescribed quasi-static loads. The steel sandwich panels consist of prismatic V-cores that are bonded to the facings using laser stake welds. Candidate sandwich panel designs are analyzed using geometrically nonlinear finite element analysis. The finite element model is validated by comparing the deflection and stresses for a representative sandwich panel with published experimental and numerical results. Sandwich panels are optimized for multiple, conflicting objectives using an integer-coded non-dominated sorting genetic algorithm. The methodology is illustrated through two optimization case studies. In the first study, we consider a rectangular steel sandwich panel configuration in which the facing segments are bonded to the core segments using double welds and optimize the panel geometry to minimize its deflection and mass. The second optimization study concerns a square steel sandwich panel in which the facings are bonded to the core segments using a single weld. The results demonstrate that the proposed methodology can be used to design lightweight laser-welded steel sandwich panels with superior structural performance.

1. Introduction

It has long been known that sandwich structures composed of stiff outer layers connected by a relatively low-density core result in high specific strength and stiffness, leading to substantial design advantages. Properly designed steel sandwich panels offer substantial resistance to static and dynamic loads due to their high relative stiffness and inherent energy absorbing capacity. To that end, steel sandwich construction has great potential for use in ships, building and bridge structures, especially for hazard reduction in situations of high wind, storm surge, earthquakes or accidental blast. Lok and Cheng [1] listed several other advantages of steel sandwich construction including the simplification of traditional connection processes, accurate construction, less surface distortion, better retention of pressure and low water leakage, greater flexibility for designers to create elegant curves, and ease of material transportation. They also noted that difficulty in fabrication and reliability of the face-sheet/core connection has been a continual problem in the widespread use of steel sandwich panels.

Laser welding techniques, especially where laser and gas metal arc welding are combined into a hybrid welding process, hold great promise for overcoming the manufacturing impediments that have stood in the way of steel panel fabrication [2]. Past fabrication methods for steel sandwich panels have relied upon fastening methods such as using periodically spaced screws, bolts or rivets [3], adhesive bonding [4], resistance welding [5], or brazing [6]. In comparison, laser welding of the core to the face-sheets in a steel sandwich panel system results in a robust, reliable and environmentally resistant connection that can be expected to have many years of service. In this process, the metal core is bonded directly to the metal face-sheet using a through-thickness stake weld as shown in Fig. 1 to create a continuous and reliable attachment. Laser welding can be performed at much greater speeds with production rates of 5–10 times that of conventional welding [7]. Good control over weld quality and weld profile has been demonstrated along with reduced residual stresses when compared to conventional welding [8]. Some other advantages of laser welding include ease of process automation, high productivity, increased process reliability, low distortion of the finished part and no requirement for filler materials.

The core, which is an essential element in sandwich panel construction, is used predominately to resist transverse shear force. Core designs for sandwich panels can take on many forms and shapes depending upon the intended end use [9]. Prismatic cores are preferred in sandwich construction because they are simple to manufacture and their high longitudinal stiffness makes them ideal in cases where orthotropic plate action is preferred. The configuration used in steel sandwich panels typically results in a highly orthotropic structure where it is necessary to consider the

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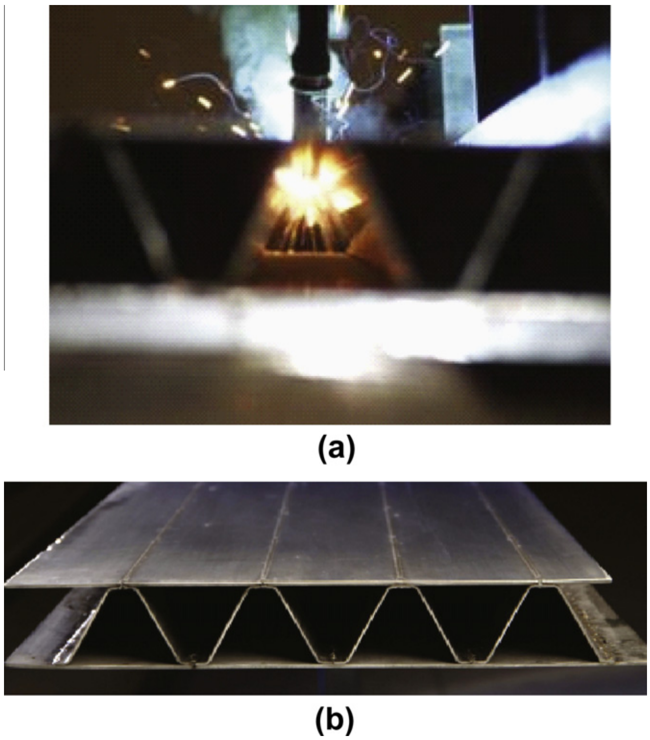

Fig. 1. Fabrication of laser welded steel sandwich panels, (a) laser stake welding of prismatic cores to facings and, (b) post production laser welded sandwich panel (Applied Thermal Sciences Inc., Sanford, Maine, USA).

effects of shear deformations even at large length to depth ratios due to the low core transverse shear rigidity [10–14]. Tan et al. [15] performed an important experimental study of a spot-welded V-core type sandwich panel and found good correlation with finite element results. The effect of a discrete face-sheet/core connection in a C-core type sandwich panel was studied by Fung et al. [16] for use in building structures. The C shaped core material they analyzed was connected to the face-sheets using screws. They modeled this connection as a line of contact and developed a mathematical formulation for the panel response including the weak axis shear stiffness, which considers the local response of the core and the face-sheet/core connection. Lok and Cheng [1] developed a mathematical formulation for truss-core type sandwich panels. They developed expressions to predict the orthotropic stiffness and quantified the effect of the core angle on the response. Chang et al. [17] presented a closed-form solution based on the Reissner–Mindlin plate theory for the bending of corrugated-core sandwich panels. The dynamic response of steel sandwich panels to intense pressure impulses has been studied by Xue and Hutchinson [18]. Fleck and Deshpande [19] investigated the blast response of steel sandwich beams and showed an order of magnitude improvement in blast resistance over monolithic beams for the case of water loads.

The advances in laser welding have made it possible to produce steel sandwich panels of different sizes and core geometries. When designing steel sandwich panels, the designer is faced with the daunting task of having to select a set of geometric parameters, such as the number of prismatic cores, thicknesses of the plate members and the corrugation angle, from a myriad of potential choices. Since the structural response and weight of a sandwich panel is highly dependent on the choice of geometric parameters, it is important to develop a robust methodology for the optimization of laser welded steel sandwich panels. Classical optimization methods, such as the gradient-based methods, suffer from certain inherent disadvantages such as a tendency to get stuck in local optima. In comparison, genetic algorithms, which belong to a class of search and optimization methods that mimic evolution through natural selection of "genetic" information, are better at finding global solutions and are easy to parallelize [20,21]. Genetic algorithms have found applications in many areas of engineering [22–26]. Klanac and Kujala [27] utilized a genetic algorithm to optimize the design of a stiffened steel cardeck. They considered two different optimization criteria, namely weight or cost of production, and obtained optimum structures for each objective separately. The design of practical laser welded sandwich panels will require the simultaneous maximization or minimization of multiple objectives. For example, we may want to minimize the weight while maximizing the stiffness. First attempts at trying to solve multi-objective optimization problems involved scalarizing the multiple objectives into a single objective using a weighted sum approach [28]. In those cases, the obtained solution is highly sensitive to the weights used in the scalarization process. However, the principles of true multi-objective optimization, where the design objectives are considered independently and simultaneously, give rise to a set of equally optimal solutions, known as Pareto-optimal or non-inferior solutions, instead of a single optimal solution [29]. Upon completion of the optimization procedure, the designer can view the manner by which the Pareto-optimal solutions are distributed in the performance space, perform trade-off studies and choose the most suitable solution based on higher level information (e.g. see Pelletier and Vel [24]).

The objective of this paper is to present a methodology for the multi-objective optimization of steel sandwich panels under quasi-static loading. Candidate designs are analyzed using a geometrically nonlinear finite element analyses via the general-purpose code ABAQUS [30]. An integer-coded genetic algorithm, based on the elitist non-dominated sorting genetic algorithm (NSGA-II), is implemented to obtain Pareto-optimal designs for multiple objectives. The finite element model is validated against experimental results presented by Tan et al. [15]. The optimization methodology is illustrated through two model problems having various conflicting objectives. In the first model problem, a 6 m $\times$ 2.1 m rectangular sandwich panel is optimized simultaneously for mass and deflection with constraints on the yield safety factor. In the second model problem, a 2 m $\times$ 2 m square panel is optimized for different loads, core heights and varying number of prismatic cores. The results demonstrate that it is possible to obtain lighter and stiffer panels through systematic optimization of geometric parameters and plate thicknesses.

2. Steel sandwich panel geometry

In the present analysis, we consider discontinuous V-core sandwich panels such as the one shown in Fig. 2a. It is more computationally efficient to model thin members of the sandwich panel as plates or shells rather than treating them as three dimensional bodies. Accordingly, the facings and prismatic core segments are modeled as thin plates about their respective mid-surfaces as depicted in Fig. 2b. The stake welds are modeled as vertical plate segments that connect the midsurfaces of the facings and core segments. The length, width and total height of the sandwich panel are denoted by L, W and H, respectively. The sandwich panel geometry is described in terms of a representative unit cell with the core segments bonded to the facings using either one or two stake welds as shown in Fig. 3. The number of prismatic cores, which is also the number of repeating unit cells across the plate width, is denoted by N_c. The thickness of the top and bottom facings are denoted by t_1 and t_2, respectively. The angle of the inclined segment of the core to the horizontal is denoted by α and the core