Available online at www.sciencedirect.com
ScienceDirect
International Journal of Mechanical Sciences 50 (2008) 69–82
International Journal of Mechanical Sciences
www.elsevier.com/locate/ijmecsci

Analysis and modeling of flexural deformation of laminated steel

Xinran Xiao*, Ching-Kuo Hsiung, Zhong Zhao

General Motors Corporation, MC 480-106-710, 30500 Mound Road, Warren, MI 48090-9055, USA

Received 15 May 2006; received in revised form 23 March 2007; accepted 17 May 2007
Available online 2 June 2007

Abstract

Steel/polymer/steel laminate sheets, commonly known as laminated steels, received attention for their superior noise damping properties in automotive applications. Published work indicates that the tensile properties of the laminated steel follow the prediction of the rule of mixtures. The flexural response of the laminated steel, however, depends on the type of the sandwich configuration. The flexural rigidity of the vibration-damping type of laminated steel is lower than the value calculated using beam theory. In industrial scale numerical simulations, automotive body panels are usually represented by using a single layer of shell element. Limited research work on finite element (FE) modeling of laminated steel has indicated that the vibration-damping type of laminated steel is better represented by using two layers of shells. It is logical to relate the simplest FE representation to the way the flexural rigidity of the laminated steel that conforms to the prediction using the beam theory. This paper examines the flexural response of the vibration-damping type of laminated steel through the comparison of beam theory predictions with the experimental results for cantilever beam and three-point bending configurations. It was found that the analytical solution for the split beam is in good agreement with the experimental results. This finding confirms the FE model that represents the vibration-damping type of laminated steel using two layers of shell with tied interface. The simulations using this method yielded good correlations with the experimental results for the two flexural loading cases studied in this paper.

Keywords: Laminated steel; Flexural deformation; Vibration-damping; Beam theory; Explicit finite element simulations; Automotive application

1. Introduction

Steel/polymer/steel laminate sheets, commonly known as laminated steel, received wide interest for their superior sound and vibration damping properties in automotive applications [1–6]. Laminated steel is composed of a thin polymer resin layer sandwiched between two steel sheet skins. The common core resins are polypropylene (PP), nylon and polyethylene (PE). According to Hayashi et al. [2], laminated steels are classified into two categories: vibration-damping sheets and light weight laminate sheets. The former typically is composed of a steel skin of 0.15–1.6 mm and a polymer core of 0.030–0.1 mm while the latter has a thinner steel skin (0.1–0.4 mm) and a thicker polymer core (0.2–1.0 mm). Fig. 1 is an illustration of the two types of laminated steel. The vibration-damping type of laminated steel is commonly known as the "quiet steel" in automotive industry.

The earlier works on the deformation behavior of laminated steel appeared in Japanese literature [7–9]. Their main findings were summarized by Hayashi et al. [2]. The tensile properties of the laminated steel follow the prediction of the rule of mixtures. The flexural response of the laminated steel, on the other hand, depends on the type of the sandwich configuration. The flexural rigidity of the light weight laminate sheet conforms to beam theory but the value of the vibration-damping sheet is lower than the calculation using beam theory.

The difference in flexural responses of the two types of laminated steel has been confirmed by finite element (FE) simulations [10]. Huang et al. [10] performed two-dimensional FE simulations of a U-bending process for four different laminated sheets, two were light weight sheets and two were vibration-damping sheets. In their FE models, both the steel skin and the polymer core layers were

*Corresponding author.
E-mail address: xinran.xiao@gm.com (X. Xiao).

0020-7403/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmecsci.2007.05.005

Nomenclature

b	width of the beam
c	elastic stress wave speed
ρ	density
σ_I	amplitude of the incident wave
σ_T	amplitude of the transmitted wave
E	elastic modulus
E_e	effective bending modulus of the laminated beam
E_k	elastic modulus of the k layer in a laminate
G	shear modulus
h	thickness of the beam
I	moment of inertia
I_k	moment of inertia of the k layer with respect to the mid-plane of the laminate
L	length of the beam
P	concentrated load
t_c	thickness of the polymer core layer in a laminated steel
t_s	thickness of the steel skin layer in a laminated steel
t	thickness of the laminated steel
w	deflection
Δl	displacement
δ	distance between the two layers of shell
γ	shear strain
τ	shear stress
ν	Poisson's ratio

modeled using triangle plane strain elements. The simulations for the two light weight sheets showed significant shear deformation in the polymer layer with no relative sliding between the layers. The simulations for the vibration-damping sheets, on the other hand, revealed relative sliding of the two skin layers.

Additional work on the flexural response of laminated steel can be found in [11,12]. Link [11] performed a three-point bending study on steel/PP/steel sheets. The three types of laminated steel reported in the paper were in the range of light weight laminate sheet. The measured flexural rigidity was close to that calculated for monolithic steel beam.

The laminated steel has a layered structure and hence may be considered as laminated plates and analyzed using laminate theory as in the case of composite laminates or sandwich structures. For vibration-damping type of laminated steel, the thin adhesive layer resembles the resin rich interface between laminas in a laminated composite which has the tendency to delaminate. The resistance to delamination growth is a subject of great interest. A common measure of this resistance is the interlaminar fracture toughness which is often characterized experimentally by loading of laminated composite beams with delamination under opening, flexural, twisting as well as combined modes [13–16]. Analytical expressions for the global load–deflection responses of composite beams with edge delamination have been derived based on the beam theory for Mode-I [17,18], Mode-II [19,20] as well as mixed mode loading conditions [21,22]. To obtain analytical expressions of stress concentration in layered structures with discontinuities requires analysis with higher order terms and advanced approaches. Stress and displacement fields near the delamination tip in laminated composites have been analyzed using transverse shear deformable laminate theory [23,24]. Various damage mechanics models have been developed which take into account damage in the layers and interface delamination fracture using the energy release rate [23], J-integral [24], continuum damage mechanics approach [25–28] and cohesive model [29]. On the other hand, the light weight type of laminated sheet may be considered as a broad adhesively bonded joint. Cohesive zone model is a popular method in modeling adhesive failure in bonded joint [30–32]. The theories and numerical methods developed in these two areas may be applied in modeling laminated steel, particularly when delamination and failure in the adhesive layer are of a prime concern.

In certain industrial applications, such as forming and crashworthiness analysis, the delamination between the skin sheets in the laminated steel is less of a concern as compared to other requirements. In forming simulations, the main objective is to predict the formability of the part [33]. In crashworthiness simulations, the main objective is to predict the safety of the passengers and the crashworthiness of the vehicle structures. This includes but is not limited to the prediction of deceleration of the vehicle due to the energy absorption by bumper system, rail

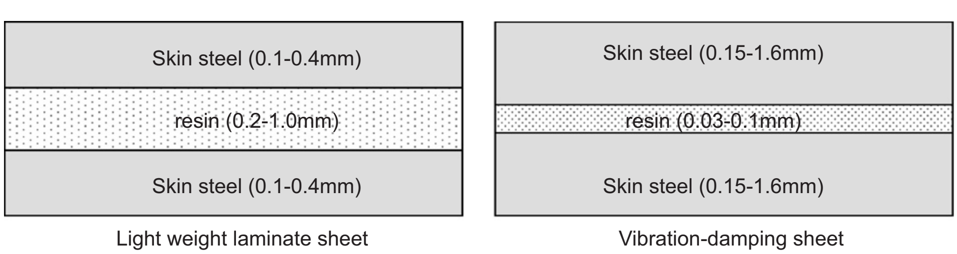

Fig. 1. Two types of laminated steel (reproduced after Ref. [2]).