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Theoretical prediction for large deflection with local indentation of sandwich beam under quasi-static lateral loading

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A B S T R A C T

By taking local indention effect and foam core strength into account in the overall deflection process, a novel theoretical model is investigated to predict the large deflection with local indentation of sandwich beam under quasi-static lateral loading. The theoretical and numerical models of lateral crushing force and total plastic energy are proposed and the theoretical results agree well with numerical and experimental results of previous researches. The results conclude that local indention phase plays an important role in initial collapse deflection of sandwich beam when maximum deflection is greater than face sheets thickness. In addition, the theoretical results with and without local indention phase of total plastic energy are compared and it shows that total plastic energy of sandwich beam will be overestimated if local indention phase is neglected. The present analytical model can predict the large deflection behavior with local indention of sandwich beam reasonably.

1. Introduction

In the recent decades, sandwich structures are widely used as energy absorbers to improve the structural crashworthiness problem in aerospace, automotive and civil engineering fields etc., by reason of largely reducing weight and keeping high specific strength and stiffness [1]. A sandwich beam is composed of a thick metallic foam core and two thin face sheets which are adhered to two sides of foam core. The large deflection response and structural mechanical behavior of sandwich structure depend on the geometries and properties of face sheets and foam core. The lateral crushing force and bending moment are supported by face sheets and the shearing force is supported by foam core of sandwich structure under lateral loading [2]. According to the design ideas of sandwich structure, many novel sandwich structures with different cores have been investigated, such as foam [1,2], honeycombs [3–5], lattice materials [6,7], corrugated structures [8,9], shell structures [10–12] and functionally graded materials [13,14] and so on. Foam core has many excellent properties such as light-weight, high energy absorption and well anti-impact capacity. Therefore, the investigation about lateral crushing force and energy absorption capacity of sandwich structure with foam core which produces large deflection behavior is significant.

The failure mode and large deflection behavior of sandwich structures under different loading were investigated in past years experimentally, theoretically and numerically. The failure modes of sandwich beam were proposed including face yielding, core shearing, face wrinkling and indentation [15–18]. A theoretical model to predict mechanical responses and central deflection of sandwich structures under impulsive loading were obtained by Zhu et al. [19]. The large deflection and energy absorption were depended on the geometry, loading, core relative density and strength of sandwich structure [2,20–22]. In addition, some novel large deflection theories were proposed by many researchers. Based on the yield criterion [23,24], an analytical model of fully clamped sandwich beam was established by using membrane factor method. The membrane force played a dominant role in sandwich beam when large deflection was greater than face sheet thickness. The theoretical results coincided well with simulation and experiment results [22,24]. Castanié et al. [25] proposed a geometrical non-linear theory of asymmetric sandwich structure and the theory was firstly validated by comparing with numerical models. The large deflection and indentation behavior of kinematic sandwich beam model with soft foam core were investigated by Hu et al. [26–28] by taking account of non-linear geometry. The kinematic model provided a reference for prediction of large deflection with indentation behavior of sandwich beam. Local indention and foam core strength are two important factors that affect the overall large deflection of sandwich beam. For local indention behavior, many experiments [15,18] and analytical models [17,29] were investigated by former researchers. Tagarielli and Fleck [18] developed a local indentation model with elastic face sheet and elastic perfectly plastic foam core. Soden [30] investigated the local indentation of sandwich beams experimentally and considered an elastic beam on a rigid perfectly plastic foundation

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theoretically. A "beam-on-foundation" model was proposed by Bostrom [31]. Based on this model, the failure was analyzed by Miller [32] when localized collapse of foam core occurred and a plastic hinge was formed in top face sheet at the edge of punch.

However, previous theoretical models of local indention are only based on small deflection hypothesis, and the associated plastic deflection only gives initial deflection with local indentation. In addition, previous theoretical models neglect neutral surface deflection which always accompanies overall deflection process. According to authors' existing knowledge, there is no further research about these problems. The major aim of this research is to investigate large deflection behavior with local indentation of a fully clamped sandwich beam under quasi-static lateral loading. By taking local indention effect and foam core strength into account in the overall deflection process, theoretical and numerical models of large deflection behavior with local indentation are proposed. The theoretical results are compared with numerical and experimental results of previous studies. In addition, lateral crushing force and total plastic energy are obtained to predict quasi-static plastic limit behavior of sandwich beam.

2. Theoretical analysis

The theoretical prediction for large deflection with local indentation of sandwich beam is proposed in this paper. Fig. 1 shows the clamped sandwich beam including top face sheet, foam core and bottom face sheet under quasi-static lateral loading. The length and width of sandwich beam are $2L$ and b respectively. The sandwich beam is loaded laterally at the mid-span by force P via a flat punch with width $2a$. The thicknesses of face sheets and foam core are h_f and h_c respectively. In the theoretical analysis, the face sheets and foam core are assumed as rigid perfectly plastic materials which obey Jones' yield criterion [33] and associated flow rule. According to established theoretical model of sandwich beam under lateral loading, the lateral crushing force and energy absorption capacity can be studied. The mechanical properties σ_f, τ_f, ν_f, ρ_f and σ_c, τ_c, ν_c, ρ_c are yield strength, shear stress, Poisson's ratio and density of face sheets and foam core respectively. The critical densification strain of foam core is ε_D.

2.1. Mechanisms of plastic collapse

The initial collapse modes of sandwich beam were investigated by Tagarielli et al. [17] and Tagarielli and Fleck [18]. Four main plastic collapse mechanisms were obtained including (i) face yielding, (ii) face wrinkling, (iii) core shearing and (iv) combined overall bending and local indentation, as shown in Fig. 2. It is note that the thickness of foam core has a directly influence on the large deflection response modes of clamped sandwich beam. For a thin foam core, face yielding and face wrinkling of sandwich beam are produced (Fig. 2(a), (b)); while for a thick foam core, core shearing and combined overall bending and local indentation are generated (Fig. 2(c), (d)). The different large deflection modes are also determined by boundary condition and materials of face sheets and foam core. For a thick beam, with increasing of lateral deflection, the membrane force plays a dominant

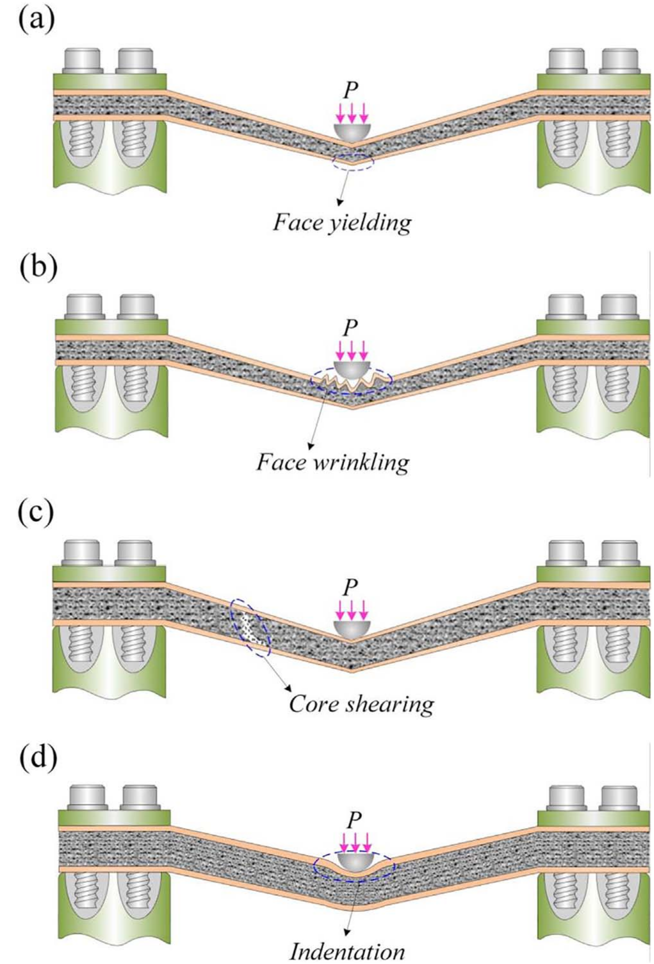

Fig. 2. The large deflection collapse behavior of clamped sandwich beam under quasi-static lateral loading: (a) face yielding; (b) face wrinkling; (c) core shearing; (d) combined overall bending and local indentation.

role in the large deflection but the effect of lateral shearing force on face sheets decreases [20,21,33]. It is assumed that the plastic collapse of fully clamped sandwich beam in the large deflection phase is determined by membrane force and bending moment.

2.2. Local indentation deflection

The analytical model of local indentation of sandwich beam under quasi-static lateral loading by a flat punch is shown in Fig. 3. The theory model of local indention in this paper is based on "beam-on-foundation" model [31,34]. The local indention deflection of sandwich beam is characterized with the increase of indentation deflection. Compared with previous theoretical model which neglects the neutral surface deflection (Fig. 3(a)), the analysis in this paper takes the neutral surface

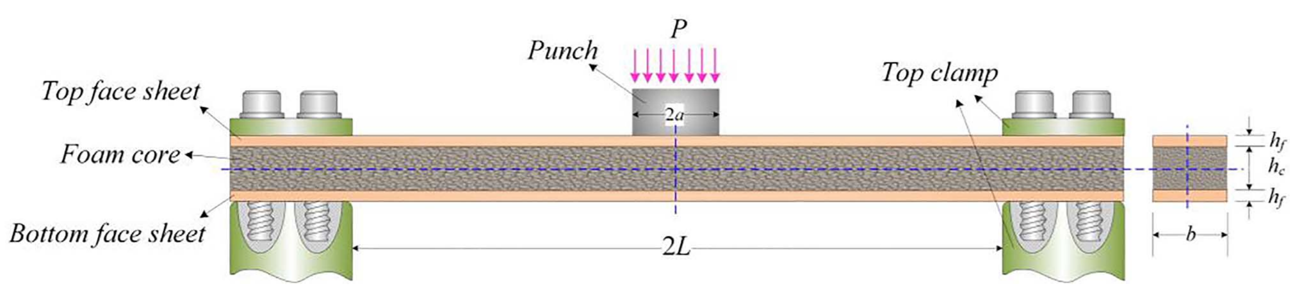

Fig. 1. The clamped sandwich beam including top face sheet, foam core and bottom face sheet under quasi-static lateral loading via a flat punch.