Low Velocity Impact Behavior Analysis of Sandwich Beam Used in Ship Structures

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Summary

The low-velocity impact behavior of sandwich beam subjected to the cylindrical impactor is investigated numerically. Finite element software ABAQUS is used, and maximum stress failure criterion and a modified stiffness degradation method are adopted to analyze the failure behavior of sandwich beam, including initiation of failure, and failure modes. The two failure modes; shear cracks in foam (Mode I), and crushed in core and damage in the top face sheets right underneath the impactor (Mode II) can be simulated well. At the range of impact velocity on this study, it can be shown that the the dynamic responses of sandwich beam are nearly quasi-static, therefore, the dynamic behavior of sandwich beam such as impact force history can be approximately obtained from static results.

1. Introduction

Owing to the advantages of lightweight and high bending strength, the composite sandwich materials play an important role in today's industry. In marine engineering, more and more small-sized ships such as fishing boats and yachts use sandwich panels in ship hull construction. However, inadvertent collision during the fabrication process, wave impact, and so on may induce damages of sandwich structures and cause significant reduction of the stiffness and strength of materials. Thus, further understanding of impact resistance, impact response and impact damage of composite sandwich is necessary for the sake of safety.

Much work has been done on impact resistance and impact tolerance of composite sandwich panels[1)-3)]. However, because of the complication of contact behavior between the projectile and sandwich panels, it is very difficult to predict the impact behavior by establishing mathematical model. A well-known approach, proposed by Tan and Sun[4)], considered for determining the impact response is to measure the local contact behavior of the panel by static indentation test, and then to use these experimental results along with an impact analytical model. The approach, however, can not be regarded as true prediction since it requires the fabrication of the entire sandwich and indentation tests made for various impactors and structures under consideration. The true prediction should possess the ability to predict the impact response from the knowledge of the behavior of individual components of the sandwich panels[3)]. Therefore, many of researches use finite element method to analyze the impact response and predict the fracture initiation of materials, however, simulation on post-failure behavior by FEM is rarely seen. The objective of this study is to develop a failure analysis procedure by FEM, which can investigate the failure modes and post-failure behavior of sandwich beam subjected to the cylindrical impactor. Maximum stress failure criterion and a modified stiffness degradation method are adopted to analyze the failure responses, and compared with the experimental results. In addition, it can be concluded that at the range of impact velocity in this study, the dynamic events can be regarded as quasi-static from viewpoints of energy and failure patterns inspected from the static and dynamic experiments. Thus, the time-consuming computation on dynamic analysis can be saved and dynamic response such as impact force history can be easily obtained once their static behavior are known.

2. Dynamic Impact Experiments And Analysis

2.1 Experiments

Sandwich panels made of laminated face sheets MAM (M: REM 300-65 glass mat; A: T-900 Aramid) and two DIVINYCELL core material with different core density 0.1, 0.2 g/cm^3 are taken into consideration. These panels are fabricated by IHI craft in Japan. The dimension of specimens is 9 cm×4.5 cm and specimen are simply-supported at two edges with a span of 6 cm.

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The mass of the cylindrical impactor is 1.52 kg and its nose-diameter is 19 mm The detailed description of test system and test procedure can be referred to Lee 5). In brief, the main failure pattern of sandwich beam with foam core density 0.1 is shear cracks in core material, located at some distance away from the impact point and with an inclined direction of 40~50 degrees. As the impact energy increases, the cracks will extend to the face-core interface, and then induce the delamination. In contrast, when foam core density is changed to 0.2, no shear cracks are found in core material, but crush in core and damage in top face sheets beneath the impact point are found. For the sake of simplicity, the failure modes of sandwich beams with core density of 0.1 and 0.2 are named as Mode I and Mode II, respectively.

2.2 Numerical analysis

The commerical finite element software ABAQUS is adopted. In order to simulate the failure behavior of sandwich beams which a mount of stiffness has been reduced, the user-defined subroutine UMAT which allows users to define a material's mechanical behavior is used as well. Because of the line load condition, the sandwich panels subjected to a cylindrical impactor can be modeled as 2-D plain strain problem. Due to the low velocity impact, the effect of strain rate is not considered here. Since the core material dominates the failure behavior, precise understanding of the response of core material to stress is required, especially the yielding or failure behavior. Gibson, Ashby, Zhang and Triantafillou[6] model the failure surfaces of cellular materials under multiaxial loads. In their papers, several statements are made by other authors; Shaw and Sata suggest that failure of foam is governed by the maximum principal stress, independent of the minor principal stress and that statement is strongly supported by Patel and Finnie and Zaslawsky. Because the micro-structure of foam considered in this study is similar to those mentioned by Ref.[6] and due to the behavior of the foam, which yields plastically under compression but cracks under tension, therefore maximum principal stress failure criterion is chosen to predict the onset of cracks and yielding in foam core. That is, when the tensile principal stress σ_1 is greater than the tensile strength of foam core X_t, cracks occur, then the corresponding elastic modulus in principal direction E_1, G_{12}, ν_{12} are reduced to zero; whereas when the compressive principal stress σ_2 is greater than the yielding strength of foam core X_c, yielding occur, then the corresponding E_2, G_{12} are modified depending on the plastic behavior of foam material.

Because the delamination and matrix crackings on laminated face sheets have little effects on failure mechanism, only fiber breakage are considered here. When fiber damage occurs in tension or in compression, degradation factors of 0.07 and 0.14 are used to modify the E_1 respectively, as suggested by Kim[7]. Fig. 1 is the impact force history of sandwich beam with core density 0.1. Because of the shear cracks occurred in foam material, the impact force history has an obvious jump. For sandwich beam with core density 0.2, the main failure pattern is slight crush in foam core right underneath the impactor and yielding the foam material, therefore, the corresponding impact force history has no force drop, but its shape becomes less symmetric as shown in Fig. 2. From Fig. 1 and Fig. 2, they also can be shown that the numerical impact force curves are in good agreement with the experimental ones. After verifying the ability of the finite element software on analyzing the failure behavior of sandwich beam, more dynamic responses of sandwich can be obtained easily and efficiently without making any experiments.

The impact energy E can be defined as $1/2\ mV_i^2$. m,

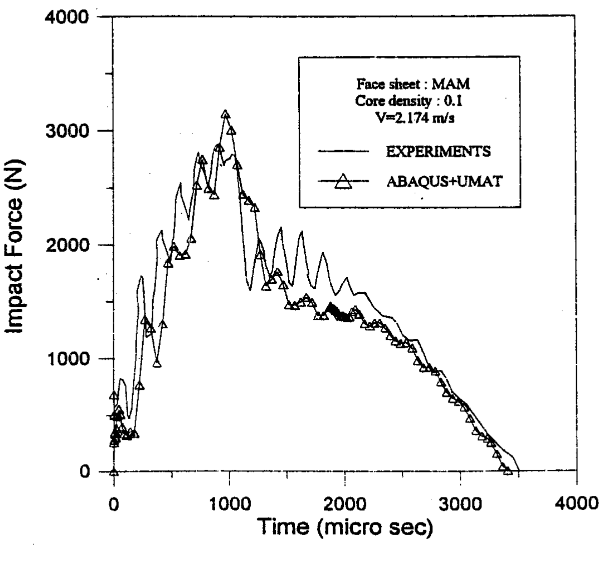

Fig. 1 The impact force history of sandwich beam with core density 0.1

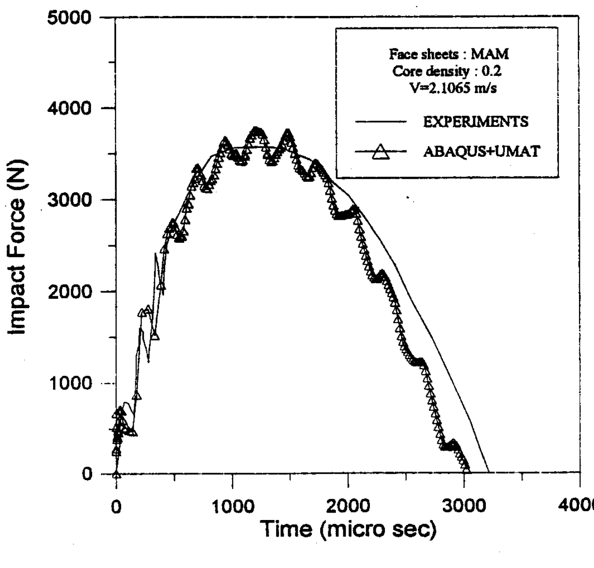

Fig. 2 The impact force history of sandwich beam with core density 0.2

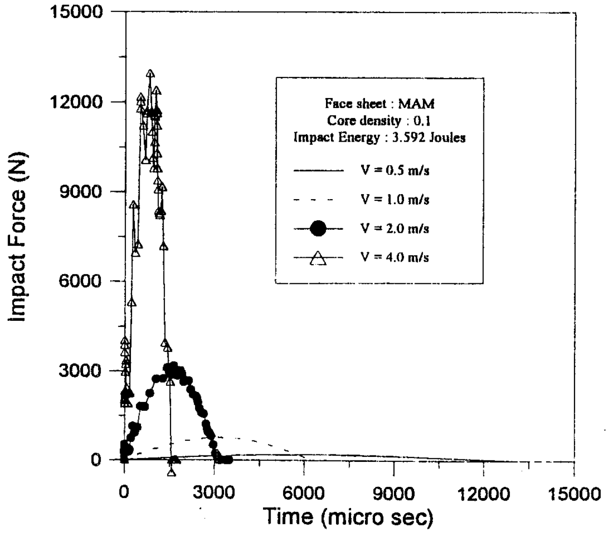

Fig. 3 Comparison on impact force histories at various impact velocities

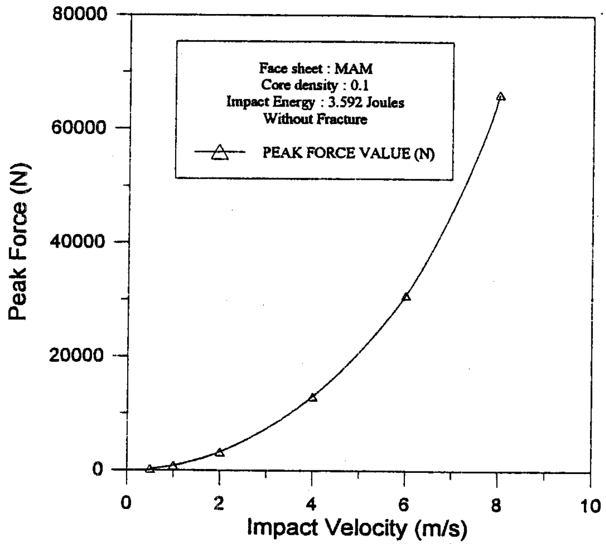

Fig. 4 The peak force value v. s. impact velocity without failure

V_i are the mass and initial velocity of the impactor, respectively. Various combination of m and V_i can results in the same impact energy, for example, larger m and lower V_i or smaller m and higher V_i. Fig. 3 is the impactor force histories under various combination of m and V_i but E is fixed to 3.592 Joules. It should be noted that no any failure are allowed in sandwich beam. From Fig. 3, it can be concluded that the higher the impact velocity is, the shorter the contact time duration is and the larger the impact force peak is. Fig. 4 illustrates the relationship between the peak force and the initial velocity of the impactor. This relationship distributes nearly a parabolic curve. However, if m is fixed to 1.52 kg, and only V_i can be changed, therefore, E would increase as V_i increases. In this case, there may be failure occurred in sandwich beam when E is

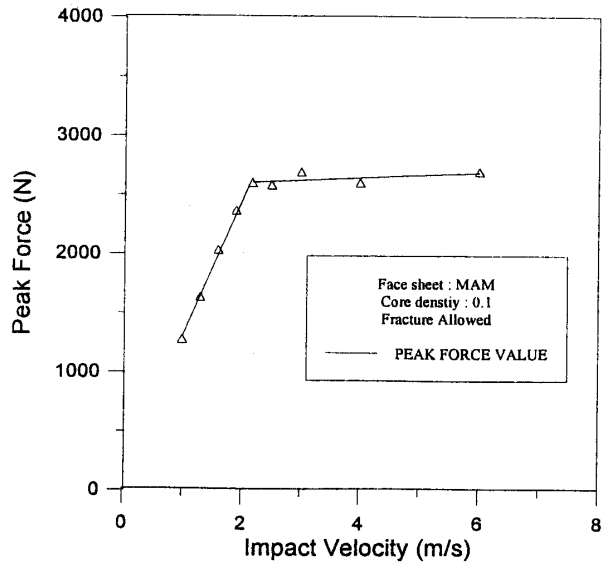

Fig. 5 The peak force value v. s. impact velocity with failure allowed

large enough.

As shown in Fig. 5, a straight line is found to fit proportionally relationship between force peak and initial velocity before any failure are formed in sandwich. But when V_i is more than 2 m/s, due to the occurrence of failure, the force peak cannot reach higher, but remains at approximately the same level. In summary, bilinear lines can describe that relationship well.

3. Comparison On Static And Dynamic Behavior

Under the low impact velocity considered in this study, the failure modes and failure patterns of dynamic cases can seem to be simulated from static cases. This conclusion can be further supported from the viewpoints of energy. In static case, the work applied to specimens by the indentor can be obtained from integrating the force-displacement curve of the indentor. The amount of this work can also be regarded as the energy absorbed by specimens under the assumption of no energy loss. In dynamic case, since the kinetic energy of the impactor almost converted to the strain energy of the specimen as shown in Fig. 6, and the vibration energy of the specimen then can be nearly ignored, hence, one way to calculate the energy absorption of specimens is by computing the loss of kinetic energy of the projectile during impact. The other way to obtain the energy absorption of specimens is to calculate the work done by the projectile in use of integrating the dynamic force-displacement curve of the projectile.

These methods to evaluate the energy absorbed by sandwich beam are compared in Fig. 7. From Fig. 7, it is surprisingly shown that three curves fit each other very well. Furthermore, at the same energy level, the energy absorbed curves are shown to be quite the same under various combinations as shown in Fig. 8 ; large

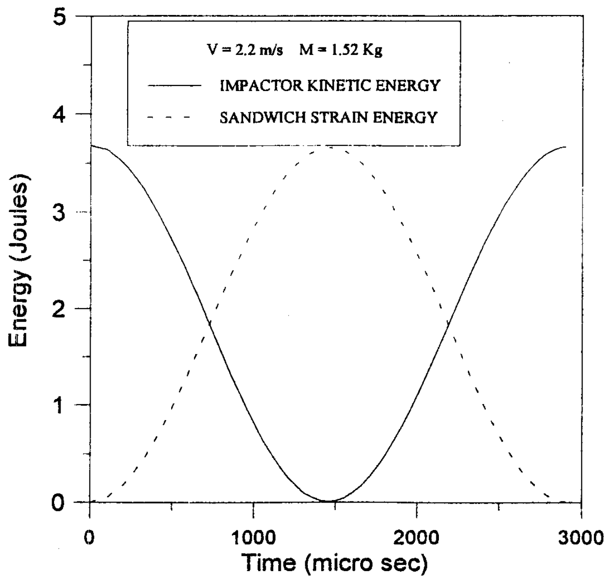

Fig. 6 Strain energy of sandwich and kinetic energy of the impactor histories

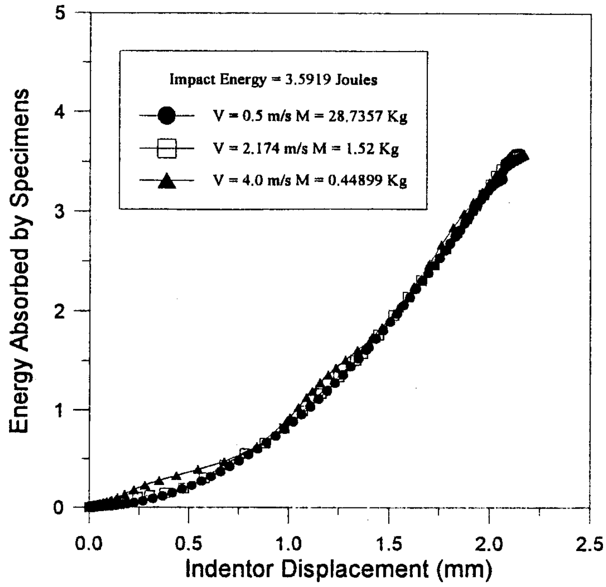

Fig. 8 Comparison on dynamic energy absorption curves at various combination of mass and velocity of the impactor

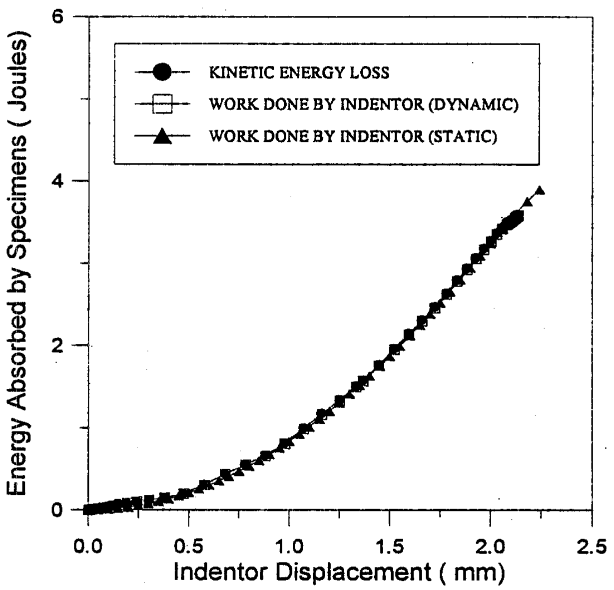

Fig. 7 Comparison on static and dynamic energy absorption curves

mass impactor with low incident velocity and small mass one with high incident velociy. From the discussion above, it can be reasonably concluded that the dynamic behavior can be approximately simulated from the static one. Therefore, the estimation whether the specimen will fail or not is easily made when the static energy absorbed curve is known. For example, the needed work done statically by indentor to lead to failure is known, saying 3.2 Joules, then for given impact velocity of 2.2 m/s and mass of the impactor of 1.52 kg, it can be predicted that specimens will fail under that impact because the value of $1/2mV_i^2$ is about 3.67 Joules larger than 3.2 Joules.

4. Static Failure Analysis

Acccording to the phenomenon that the damage patterns of sandwich beams under dynamic condition are similar to those produced under static condition, thus, only static failure analysis is conducted and described in detail. The dimensions of sandwich beams are the same as mentioned before, but the span of simply-supported condition is 8 cm and the diameter of indentor is changed to 12 mm.

4.1 MODE I

The typical static tests curve of sandwich beams with core density 0.1 indented by a cylindrical impactor is shown in Fig. 9. For convenience, several checkpoints are marked along the curve. Initially, the specimen is loaded up from checkpoint O to A, without any observable damage. Over the checkpoint A, minor matrix crackings on top face sheets and yielding of the core in the region underneath the indentor result in the reduction of bending stiffness of specimen. When the load path reaches B, the loading immediately drops from B to C due to the onset of shear cracks in core and the extension of cracks along the face-core interfaces. During the path C−D, the specimen continuously deforms without further extreme failure. The comparison between numerical and experimental F-d curves is shown in Fig. 10. It can be seen that those curves fit each other well. On the numerical F-d curve, there is a slight drop resulted from fibers breakage right over the level of A. This discrepancy is owing to the drawbacks of that method which simulates the fibers damage by multiplying a degradation factor right after the failed elements detected. The progressive illustration of simulation for shear cracks is shown in Fig. 11. It can be concluded

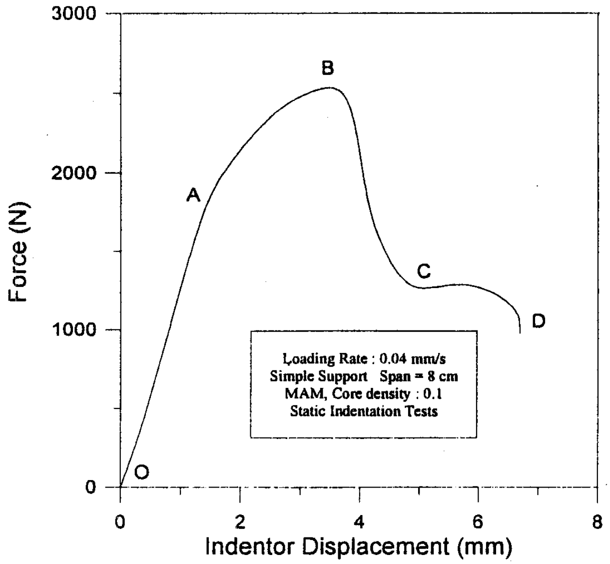

Fig. 9 The experimental F-d curve of sandwich beam with core density 0.1

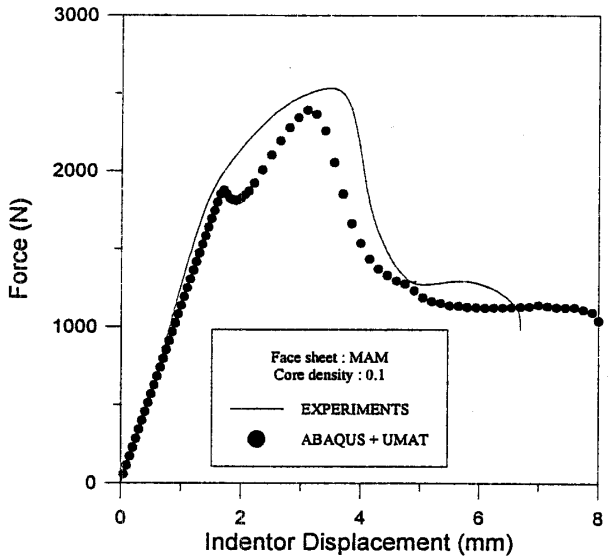

Fig. 10 Comparison on experimental and numerical F-d curves of sandwich beam

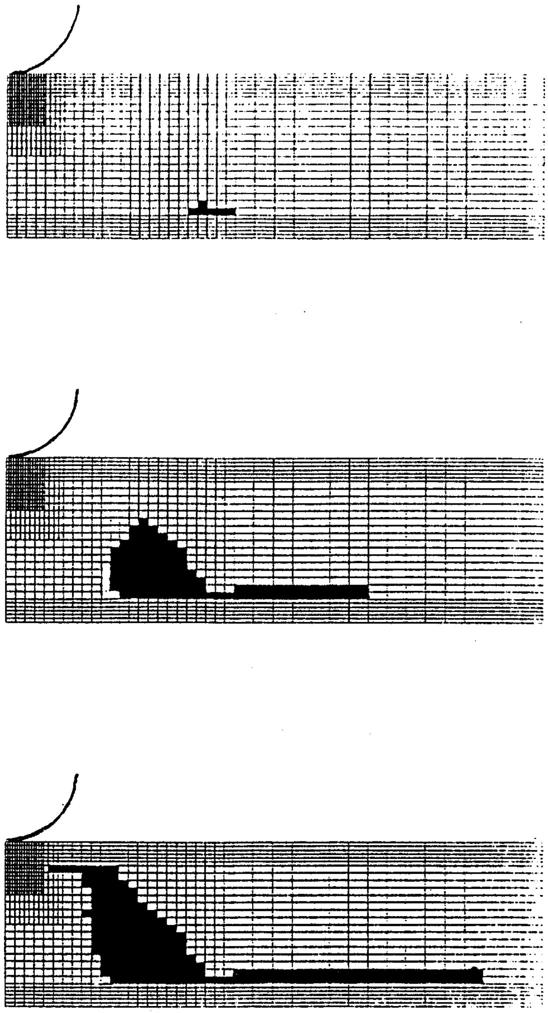

Fig. 11 The progressive failure pattern in core of sandwich beam

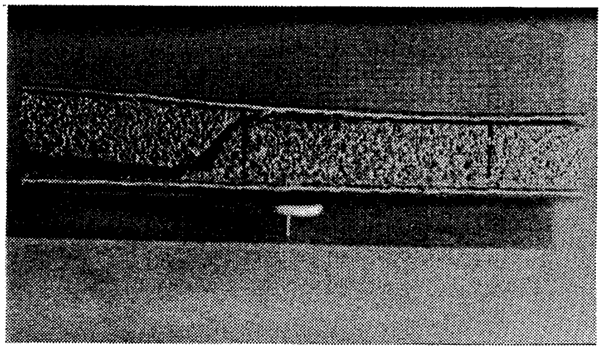

Fig. 12 Photo of Mode I failure pattern obtained by experiments

from Fig. 11 that the progressive crack failure pattern is in consistence with the one observed during experiments. Fig. 12 is the photo of Mode I failure pattern obtained by experiments.

4.2 MODE II

When the core density is changed to 0.2, under the same configuration and loading condition, the failure patterns of sandwich beams are different from those of Mode I. From Fig. 13, the specimen is loaded from O to A without any failure, however, over the level of A, the core exhibits plastic behavior and face sheets are damaged in the region right under the indentor. As going further along the path A−B, the degree of plasticity in core and damage in face sheets grows continuously. When checkpoint B is reached, fibers of top face sheets beneath the indentor are almost broken totally and a vertical crack located in the center line of the core is found. As the loading path moves, the crack propagates downward and the loading-carrying capac-

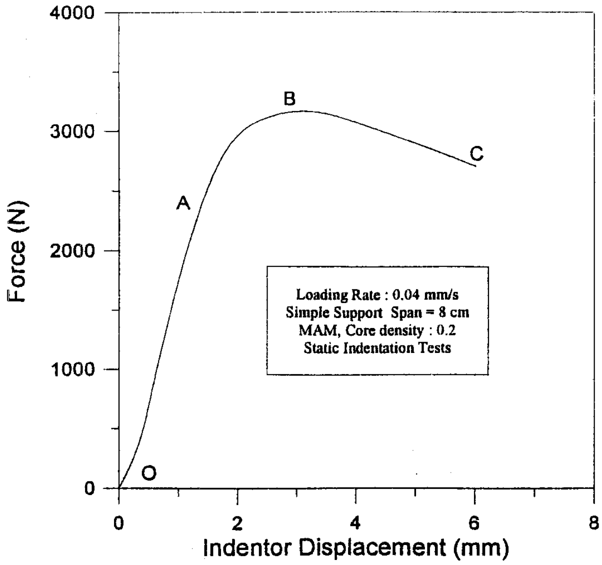

Fig. 13 The experimental F-d curve of sandwich beam with core density 0.2

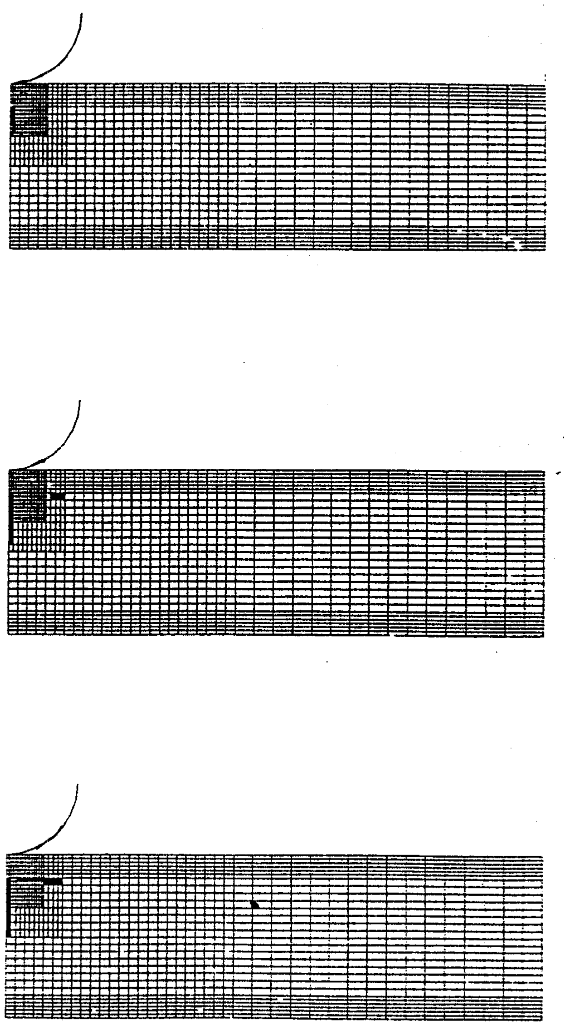

Fig. 14 The progressive failure pattern in core of sandwich beam with core density 0.2

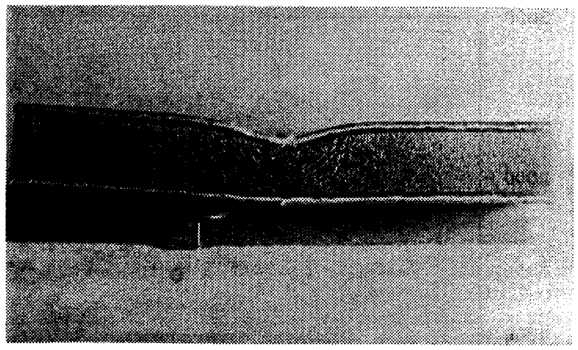

Fig. 15 Photo of Mode II failure pattern obtained by experiments

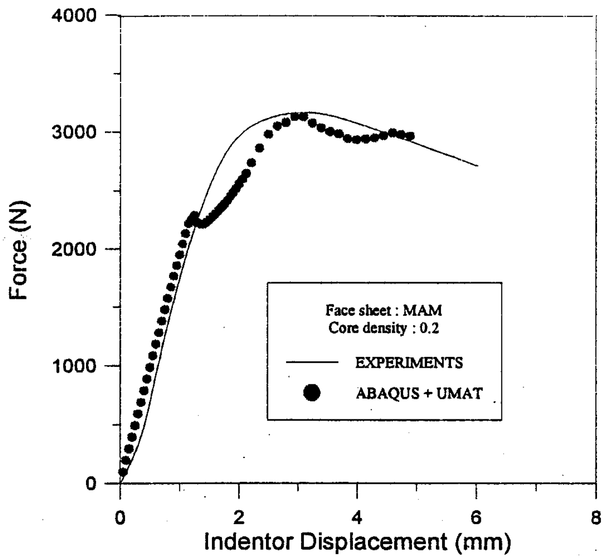

Fig. 16 Comparison on the experimental and numerical F-d curves of sandwich beam with core density 0.2

ity of specimen loses gradually as seen in path B–C. The progressive crack failure pattern in core material is illustrated in Fig. 14 and the experimental photo of Mode II is shown in Fig. 15. The comparison on computational and experimental F-d curves is shown in Fig. 16. Although these curves are generally in consistent with each other, however, as mentioned before, the modeling on fibers damage needs to be further improved.

5. Static impact force history

As concluded above, at the range of the impact velocities in this study, the dynamic behavior of sandwich beam belongs to *quasi-static*, therefore, the dynamic responses can be simulated from static ones. For example, if the static indentation curve (F-d curve) is known, then the impact force history (F-t curve) and displacement history (d-t curve) can be easily obtained in use of several simple equations. The proce-

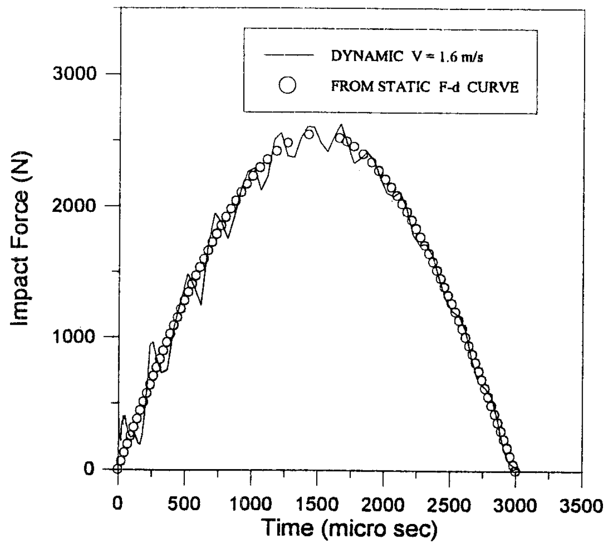

Fig. 17 Comparison on dynamic and static impact force histories without failure

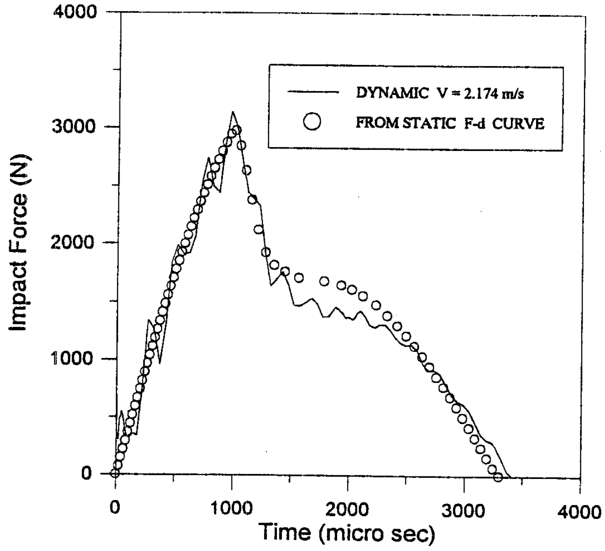

Fig. 18 Comparison on dynamic and static impact force histories with failure occurred

dure to get the impact force history from static F-d curve is described briefly as follows;

Step 1. Integrate the F-d curve and use eqn (1), then V-d curve can be obtained. Where, m, V_i are defined as before, V is the impactor velocity during impact.

$$W=\int F\Delta d=\frac{1}{2}m(V_i^2-V^2) \quad (1)$$

Step 2. Use V-d curve and eqn (2), then $\Delta t-d$ curve can be obtained

$$\Delta t=\frac{\Delta d}{V} \quad (2)$$

Step 3. Summarize the Δt, then t-d curve can be obtained.

Step 4. Incorporate F-d curve and t-d curve by eliminating d, then *static* impact force history can finally be obtained.

Fig. 17, Fig. 18 are the comparison between *dynamic* and *static* impact force history when the impact velocities are 1.6 m/s and 2.174 m/s, respectively. Those curves fit each other quite well except that the oscillation phenomenon existed on dynamic impact force history can not be produced from static F-d curve. It can be concluded from Fig. 17 and Fig. 18 that the procedure really can work no matter the sandwich beams would fail or not. Similarly, other dynamic responses also can be obtained this way, and therefore, the computing time for dynamic analysis can be greatly reduced

6. Conclusion

To simulate the failure mechanism of sandwich beams subjected to a cylindrical impactor, the maximum principal stress criterion and a stiffness degradation method are coded into the user-defined subroutine UMAT provided by finite element software ABAQUS. This failure analysis procedure can precisely model two of different failure modes; Mode I: shear cracks in core and Mode II: yielding in core and damage in top face sheets right under the indentor. In the range of impact velocity considered in this study, it can be concluded that the dynamic behavior can be simulated from static results from the viewpoints of energy. Under this conclusion, the dynamic responses such as the impact force history can be approximately obtained from static F-d curve of the indentor without any time-consuming dynamic calculation.

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