EXPERIMENTAL STUDY OF LOW VELOCITY IMPACT ON SANDWICH PANELS WITH HONEYCOMB CORE AND COMPARISON WITH THE F.E.M RESULTS

Niaz Abdolrahim [1], Gholamhossein Liaghat [1], Hesam Aldin Askari [2]

Department of mechanical engineering, Tarbiat modares university,P.O. Box 14115-111, Tehran, Iran
Department of mechanical engineering, Iran University of Science and Technology, Narmak, Tehran, Iran

ABSTRACT

The problem of impact on the sandwich panels with glass-epoxy face sheets and aluminum honeycomb core has been studied. At first both analytical and numerical solutions were explained and then the results of these two ways were compared with experimental test results. In analytical solution, after considering other author's researches, an improved model has been presented. Analytical model for low velocity impact on sandwich panels is performed basically on static solutions for both rigid and four sided clamped supports. The model was modified by considering the strain rate effects in dynamic load cases. In numerical solution the model was completely simulated in ANSYS/Ls-Dyna. The sandwich panels were prepared with composite face sheets of glass-epoxy and aluminum honeycomb cores, in two different sizes. With experimental results the effect of some parameters like energy of impact, different types of supports, thickness of composite laminates and shape of projectile on producing damage during the impact process, has been studied. Finally force-time history of results of both analytical and numerical solutions and their applications has been compared to experimental results in some different load cases.

Key words: Impact, Sandwich panel, Honeycomb, Composite, Finite element method, Crushing resistance

1. INTRODUCTION

One of the most important reasons of ever increasing usage of honeycombs in structures is their low weight and high stiffness. The wide usage of sandwich panels in space industries improves the importance of understanding the mechanism of initiating damage due to impact and the effect of this damage on the efficiency of the panels. Experimental studies demonstrated that the visible core crushing is the first failure mode, occurs in sandwich panels with the high skin-core ratio. A lot of authors were worked in experimental and numerical solutions. But due to the complexity of behavior of the sandwich structures during deformation and failure, a few of them have worked on theoretical studies.

Goldsmidth and Sackman[1] investigated experimentally on absorption characteristics of honeycombs and sandwich panels with honeycomb core due to impact of flat top projectiles. Their tests were done both statically and dynamically and the loading was along the axes of honeycomb. Wierzbicki et. al [2] studied the absorption characteristics of impact energy in sandwich plates with honeycomb core, theoretically[3]. They neglected the bending stiffness of the face sheets and considered only the membrane characteristics of the laminates. They assumed that the resistance of the sandwich plates is because of three sources including the crushing of honeycomb just under the projectile, crushing of honeycomb outside the contacting area of the projectile and face sheet due to the face sheets and membrane stiffness of the face sheets. Khalili, Malekzadeh and Mittal [4] demonstrated a new solution based on improved higher order sandwich plate theory (IHSAPT) and two models for simulating the contact behavior of projectile and panel during the low velocity impact on sandwich panels with flexible core and composite face sheets. Karger and his colleagues [5] developed a software code named CODAC, for simulating the low velocity impact on sandwich panels. They compared the force-time history and size of the failure area with the experimental results. Fatt and Park [6,7] studied on damage initiation on composite sandwich panels and compared their results with the Wen and his colleagues results [8]. The failure modes that they assumed included core shear failure, shear and tensile failure of the top face sheet and tensile failure of bottom face sheet. In this study we used their formulation in the theoretical solution.

2. STATIC ANALYSIS

The composite sandwich panels are symmetric and consist of orthotropic laminate face sheets and a core with constant crushing strength. These assumptions are true for honeycomb cores made of aluminum, nomex and some foam cores [9]. Sandwich panels are supported 1) rigidly supported (bottom face sheet is fixed) 2) four sided clamped. Four sided clamped sandwich panels have two kinds of deformations, local and global. Local deformation consists of top face sheet indentation and core crushing. Global deformation consists of bending and shear of entire panel. Rigidly supported sandwich panels have no global deformation but only local deformation.

Approximate static analysis of global deformation is produced by minimizing the potential energy. This solution is achieved by deformation profile of a sandwich panel. Generally in small deformations just bending loads and in large deformation (more than half of the thickness of top face sheet) just the membrane loads can be considered. This assumption is very important, unless otherwise the formulations become very complex and the analytical solution is very difficult.

2-1. Sandwich panels with rigidly supported boundary conditions

2-1-1. Plate on rigid-plastic foundation (considering bending stiffness)

Fatt and Park[6] obtained the load-indentation response by using the principle of minimum potential energy. Minimizing the potential energy, the system is stable statically. The force-indentation response is given by

$$P = 32\sqrt{\frac{2}{255}D_1 q\delta} + \pi q R^2 \qquad (1)$$

$$D_1 = \frac{16384}{11025}\left(7D_{11} + 7D_{22} + 4D_{12} + 8D_{66}\right)$$

2-1-2. membrane on rigid-plastic foundation (considering membrane stiffness)

Considering only the membrane stiffness, the force-indentation response is given by:

$$P = 8\frac{\sqrt{8C_1 q}}{3}\delta^{\frac{3}{2}} + \pi q R^2 \qquad (2)$$

$$C_1 = 8\left[\frac{1}{45}\left(A_{11} + A_{22}\right) + \frac{1}{49}\left(2A_{12} + 4A_{66}\right)\right]$$

A rigidly supported sandwich plate can be approximated by a single degree-of-freedom system consisting of projectile mass M_0**,** effective mass of face sheet m_f , a nonlinear spring and a constant force dashpot as shown in figure (1a).

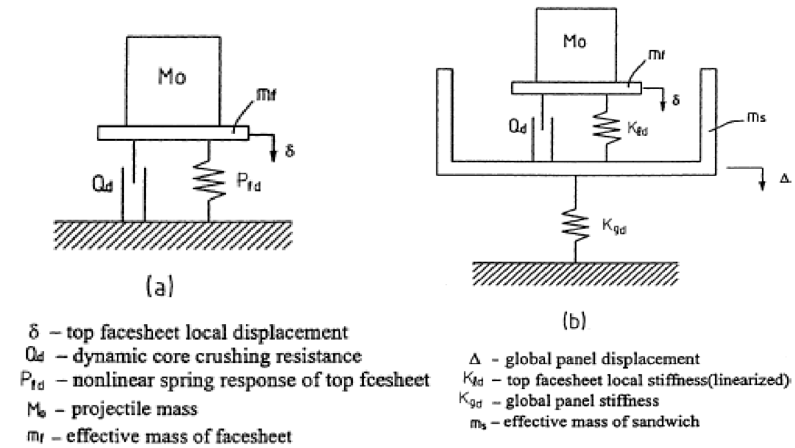


Fig.(1). Discreet modeling of a rigidly and clamped supported sandwich panel [6]

The local transient response can be obtained by the following differential equation:

$$M_o\ddot{\delta}+P_1(\delta)+Q_d=0 \tag{3}$$

The solution of this equation can be obtained by using the initial conditions $\delta(0)=0$ & $\dot{\delta}(0)=V_0$. The impact force is calculated by:

$$F(t)=-M_0\ddot{\delta}(t) \tag{4}$$

The maximum force occurs at $t_{\max}$ when $\dot{\delta}=0$ and is given by:

$$F_{\max}=-M_0\ddot{\delta}(t_{\max}) \tag{5}$$

2-2. Sandwich panels with clamped supported boundary conditions

As shown in figure (1b) the dynamic response of a clamped panel is described by the coupled two degree of freedom as the following equations:

$$(M_0+m_f)(\ddot{\Delta}+\ddot{\delta})+P_1(\delta)+Q_d=0 \tag{6}$$

$$P_1(\delta)+Q_d=m_s\ddot{\Delta}+K_{gd}\Delta \tag{7}$$

Solving equations (6)& (7), δ is given by :

$$\delta=\frac{\dot{\delta}_0}{\omega}\sin\omega t+\frac{Q_d}{K_{1d}}\cos\omega t-\frac{Q_d}{K_{1d}} \tag{8}$$

And

$$\omega=\sqrt{\frac{K_{1d}K_{gd}}{(K_{1d}+K_{gd})M_0}} \tag{9}$$

$$F(t)=-M_0(\ddot{\Delta}+\ddot{\delta})=-M_0\left(1+\frac{K_{1d}}{K_{gd}}\right)\ddot{\delta} \tag{10}$$

3. F.E.M modeling and analysis

3-1. Modeling geometry and meshing

Geometrical modeling consists of 3 parts: 1) projectile 2) composite layers 3) honeycomb core. Shell element is used for meshing the sandwich panel surfaces in two types of composite for two surfaces and non composite for honeycomb core. Shell163 is a 4 node element with both membrane and bending capabilities. Both in plane and normal loads permitted. The formulation used for this element is Belytchko-Tsay. The projectile is modeled by a 3d structural 8-node element called solid164.

3-2. Material characteristics and failure criteria

3-2-1. Projectile

For modeling the projectile the steel characteristics were used. The diameter of the projectile is 12.7mm and its weight is 7.5kg.

3-2-2. Composite plates

In composite plates the failure modes due to transverse impact include matrix tensile cracking, matrix compressive/shear failure, fiber matrix rebounding, fiber breakage (compressive or tensile), delamination and etc. Fiber breakage is very important due to reduction of the residual stiffness [10]. Delamination that can be easily visible usually doesn't occur in tests. Therefore the glass-epoxy composite laminate is modeled as an orthotropic material with damages including matrix cracking, compressive failure and fiber breakage failures. In numerical modeling the 55th material of ANSYS called Composite Damage. Chang-Chang criterion [11] is used for this material model.

3-2-3. Honeycomb core

The stress-strain curve of the Nomex core material that is shown schematically in Fig.2 can be divided in to three regimes:1) at low strains (0.5-5%) a linearly elastic region, 2) a region corresponding to progressive crushing at nearly constant stress level (the 'plateau stress' σ_{pl}), and 3) a region of rapidly increasing stresses with further deformation due to the fact that the cell walls are forced into contact with each other.

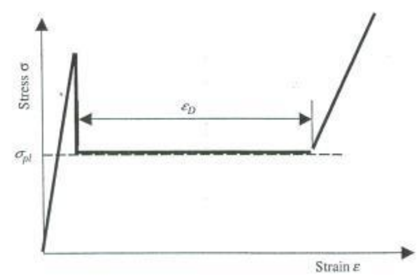


Fig.(2). Schematic stress-strain curve of the Nomex honeycomb core [12]

For high density honeycombs, the linearly elastic region ends when the honeycomb cell walls start fracturing. The initiation of elastic buckling does not cause a complete loss of stiffness since after the initial fracture of the cell walls is observed, a sudden drop from a collapse stress to a steady crush strength occurs. Also small oscillations may occur about the mean stress value due to consecutive local buckling. The 'densification strain' ε_D typically ranges from 50% to 80%. The area under the stress–strain curve up to densification is the useful energy that can be absorbed per unit volume and will be illustrated as follows [12]:

$$W_V = \sigma_{pl} . \varepsilon_D \tag{11}$$

Due to real geometrical modeling of honeycomb core, the material model called Johnson-Cook [13] can be used for its material that is Al5052. This model also called viscous plastic model, is a strain-rate and adiabatic (heat conduction is neglected) temperature-dependent plasticity model. Temperature changes due to plastic dissipation cause material softening. Johnson and Cook express the flow stress as:

3-4. Modeling contacts and the joints between the core and plates

The contact models are including:

a) Contact between the projectile and composite plate

b) Joint between composite plate and core, that is for modeling the adhesion between the composite plate and core and characterized by following formulation:

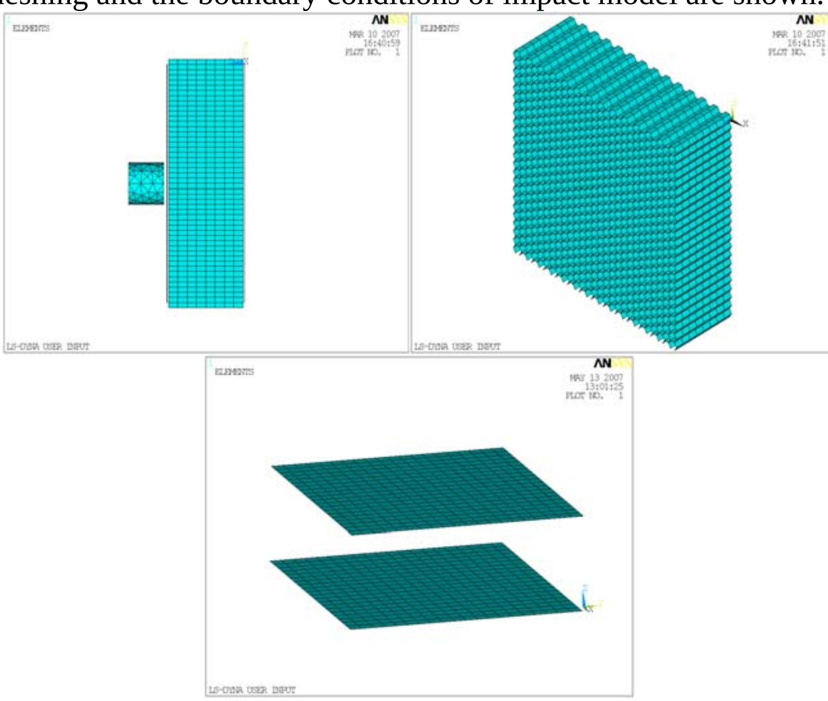
$$\left[\frac{\max(0,0,F_{normal})}{F_S}\right]^2 + \left[\frac{F_{shear}}{F_D}\right]^2 - 1 > 0 \qquad (12)$$

While F_{normal} and F_{shear} are the transverse and shear force and F_S and F_D are the transverse and shear stiffness between the composite plate and honeycomb core.

c) In the case of disjoining/rebounding of this joint and exceeding of the related force more than the defined limitation and validity of equation no.12, the joint is discarded and a contact is assumed between the composite plates and core.

3-5. Boundary conditions and initial velocity

According to different boundary conditions (rigidly and four sided clamped supported) in different tests, the boundary conditions are applied to the concerning nodes. The initial velocity of the projectile is assumed considering the energy level and the velocity of projectile just before the impact, in each test. Because the accelerations that applied to the projectile during impact are much higher than gravity, it can be neglected. In figures (3) geometry, meshing and the boundary conditions of impact model are shown.



Fig(3). Geometry and meshing of sandwich panel and projectile

4. Construction, coding and testing of samples

Mechanical properties of composite plates, aluminum honeycomb core and projectile are presented in table (1).

Table (1), Mechanical and geometrical properties of composite plates, aluminum honeycomb core and projectile

Face sheet Glass/Epoxy woven fabrics $150\times150mm^2$ and $a\times a=75\times75mm^2$ $h=1.15mm\ and\ 2mm$ $\rho=1700kg/m^3$	Ply stiffness $E_{11}=17GPa$ Longitudinal stiffness $E_{22}=17GPa$ Transverse stiffness $E_{33}=E_{22}=17GPa$ $G_{12}=4GPa$ in-plane shear modulus $G_{13}=G_{23}=1.5GPa$ $\upsilon_{12}=0.046$ Poisson's ratio $\upsilon_{23}=0.2$ Ply Strength $X_T=250MPa$ $X_c=250MPa$ $Y_c=Z_c=204MPa$ $S_{xy}=47MPa$ $S_{xz}=\tau_{13}=70MPa$ static out-of-plane shear strength $S_{yz}=70MPa$ $\varepsilon_{cr}=0.021$ static tensile failure strain
Core Honeycomb AL 1/8-5052-3.1	$\rho=50\ kg/m^3$ mass density $H=25.4mm$ Core thickness $q=\begin{cases}5.72\ MPa\\4.94\ MPa\end{cases}$ Crush resistance $E_{11}=1.24\ MPa$ $E_{22}=0.2\ MPa$ $E_c=517\ MPa$ Young's modulus $G_c=0.31GPa$ Shear modulus $\upsilon_c=0.7$ Poisson's ratio
Indenter/Projectile Blunt and hemispherical made of V.C.N steel	$D=12.7mm$ $M=7.5kg$

Coding of samples were conducted according to table (2).

Table (2), Coding of samples in accordance with different test conditions

	Energy of impact	Boundary conditions	Thickness of composite plates	Type of projectile
1	5J	$a\times a=75\times75mm^2$ clamp	1.15mm	Blunt
2	8.1J	$a\times a=150\times150mm^2$ clamp	2mm	Hemispherical
3	10J	$a\times a=75\times75mm^2$ rigid	- - - -	- - - -
4	15J	$a\times a=150\times150mm^2$ rigid	- - - -	- - - -
4	20J	- - - -	- - - -	- - - -

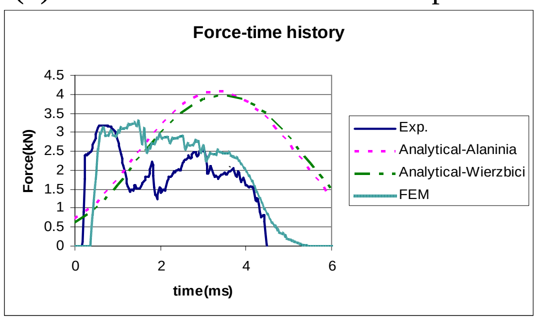
For instance a sample with the code of 2412 has the following characteristics:

Energy of impact	Boundary conditions	Thickness of composite plates	Type of projectile
8.1J	$a\times a=150\times150mm^2$ rigid	1.15mm	Hemispherical

5. Results and discussion

5-1. sandwich panel with rigidly supported boundary conditions and composite plate thickness of $1.15mm$

Due to large deformation of top plate, comparing to its thickness before the initiating of any damage (larger than half of its thickness) and according to mentioned topics, the sample is under membrane tension and is assumed as a membrane on a plastic bed. In this situation after considering the strain rates, the dynamic membrane stiffness is assumed equal to the static one $C_{1d} = C_1$. Therefore in this case the equations (2) and (3) are used for predicting the variations of impact force in accordance with time. In fig. (4), the force-time history of a sample that has been tested with the energy of $5J$, is shown and the results of three approaches(numerical, analytical and experimental) are compared with each other. Also in table (3) the maximum forces are compared.



Fig(4). Force-time history of sample 1311 with the impact energy of $5J$ and comparison the results of numerical, analytical and experimental approaches

Table (3). Comparison of the maximum impact energy

Impact energy (J)	Maximum impact energy (KN)			
	Exp.	FEM	Analytical (Alavi-Nia)	Analytical (weirzbicki)
5	3.2	3.3	4.08	3.9

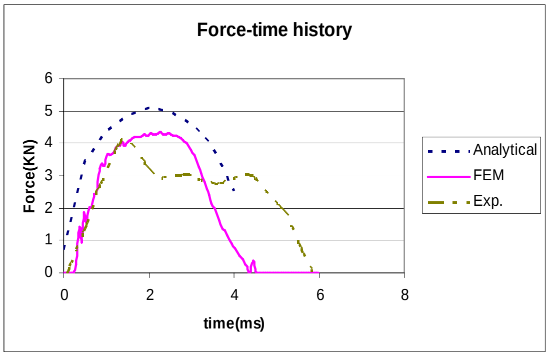
5-1-1. assessment of results

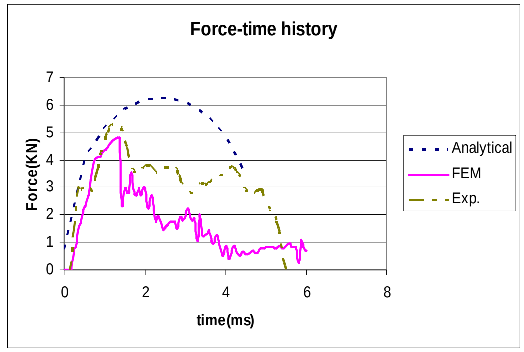
Considering the presented curves and table, one can conclude that the numerical results are more accurate than analytical ones. At the energy level of $5J$, there is no failure can be seen top plates and just a little deformation is occurred in it. By increasing the energy level up to $10J$, the damage of the top plate increases too and the analytical results that predict the results before the damage, lead to high errors. At the energy level of $15J$, the panel sandwich fails completely, the projectile penetrate and the top plate plugs.

5-2. Sandwich panel with rigidly supported boundary conditions and composite plate thickness of $2mm$

In this case, because the deformation of top plate comparing its thickness is negligible (smaller than half of the thickness), in contrast of the previous case, the sample is under bending and is assumed as a plate on a plastic bed. In this case after considering the strain rates, the dynamic bending stiffness is assumed equal to the static one $D_{1d} = D_1$. Due to increasing the thickness of plates comparing the previous one, the tests held on with higher energy levels. In fig. (5a&b), the force-time history of a sample that has been tested with the energy of $5J$ &$10J$, are shown and the results of three approaches

(numerical, analytical and experimental) are compared with each other. Also in table (4) the maximum forces are compared.





(a) (b)

Fig(5). Force-time history of a) sample 1321 with the impact energy of $5J$ b) sample 3321 with the impact energy of $10J$ and comparison the results of numerical, analytical and experimental approaches

Table (4). Comparison of the maximum impact energy

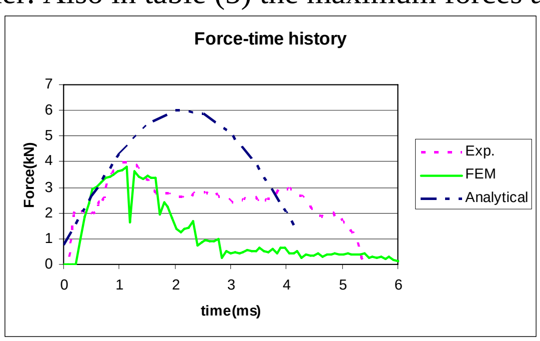
Impact energy(J)	Maximum impact force (kN)		
	Experimental	FEM	Analytical
5	4.1	4.3	5.1
10	5.4	4.8	6.2

5-2-1. assessment of results

In this case the numerical results are more accurate than analytical ones too. It can be seen that again the results are more accurate in energy level of $5J$ and by increasing the energy and impact velocity, the accuracy decreases. The sample with the thickness of $2mm$ will fail completely at the energy level of $40J$ and the projectile penetrates and the top plate plugs.

5-3. sandwich panel with 4 sided clamped supporting boundary conditions and composite plate thickness of $1.15mm$

In fig. (6), the force-time history of a sample that has been tested with the energy of $10J$, is shown and the results of three approaches(numerical, analytical and experimental) are compared with each other. Also in table (5) the maximum forces are compared.



Fig(6). Force-time history of sample 3111 with the impact energy of $10J$ and comparison the results of numerical, analytical and experimental approaches

Table (5). Comparison of the maximum impact energy

Impact energy (J)	Maximum impact force (kN)		
	Experimental	FEM	Analytical
10	4	3.8	6.9

5-3-1. assessment of results

It can be seen that in 4 sided clamped supporting, in spite of comparing the results for energy of $10J$, the produced damage in top plate is very low and numerical results are very accurate again. The steps that are shown in numerical curve are representatives of producing cracks and dramatic decreasing the stiffness under the projectile that lead to sudden decreasing of force. However due to the produced damage and the fact that the analytical solution is based on seeing no damage in plate, the errors of analytical model has increased dramatically comparing with previous tests.

5-4. arguing the results

In the previous part analytical and numerical solutions were compared with experimental test results.

According to the curves one can find that the theoretical force almost always starts from a value near zero and ends near that value too. Due to considering the model as a membrane on a plastic bed, at the time of the initiation of impact the core initiates to crush and that primary value is the force that is needed for crushing the core and equals to:

$$F_0 = Q_d = \pi R^2 q_d \approx 722\,kN$$

- In samples with lower thickness of composite plate, the behavior is mostly like a membrane tension and in samples with higher thickness of composite plate, the behavior is mostly like a bending plate and a smaller local deformation occurs in this case.
- The software ANSYS/Ls-Dyna that was used for numerical solution, was omitting the damaged elements. Although this job was a good approximation for simulating the degradation of the material properties, by omitting the element the material properties is considered to be zero in that place. This is not the thing that is happened in reality.

6. Conclusion

By assessment of the results the following points may be concluded:

- Analytical solutions had errors in ranges of about (14-22%) due to basis of static assumption. By increasing the impact energy the errors becomes more (up to 22%) because of receding of the model from static assumption.
- Numerical solutions showed good compatibility with experimental results. The error ranges was about (3-12%). By increasing the impact energy the errors becomes more (up to 12%).
- The most important damage mode that was observed in tests, was the failure of the top plate that could lead to severe degradation of material properties, while the first damage mode that occurred almost in all tests was the shear failure of the core.
- The aim of this investigation was to show that a correct numerical model can give enough information for designing a resistant structure to impact for a designer. Also the analytical solutions can give some helpful information for predicting a primary approximation of the force-time history in the design process.

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