構造用 샌드위치 板의 휨特性에 對하여

Flexural Behavior of Structural Sandwich Panels

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적　요

구조용 샌드위치판이라는 것은 두꺼운 경량재료를 가운데 두고 그 양면에 얇은 표면재료를 부착시켜서 만든 구조재료의 일종이다. 이와같은 일종의 합성재의 개념은 서로 다른 성질의 재료를 부착제에 의하여 조합시킴으로써 각각의 재료가 독립적으로는 발휘하지 못하는 휨에 대한 저항 기능을 발휘할 수 있도록 하는 것이다.

이 연구의 목적은 구조용 샌드위치판의 휨특성을 결정함에 있어서 이론적인 계산과 실험적인 방법을 비교하고자 하는 것인데 그 결과는 다음과 같다.

1. 샌드위치 판의 중앙점의 휨량은 해석적으로 유도한 공식에 의하여 근사적으로 계산할 수 있다. 이때 탄성상수들이 주어져야 한다.
2. 부착제의 질을 개량하므로써 전체적인 휨 剛度 및 휨 強度를 증가시킬 수 있다.
3. 샌드위치판의 최대 휨량과 응력을 계산하는 가장 간단화 된 공식은 본 실험에 사용된 치수의 범위에서는 설계 목적에 사용될 수 있다.
4. 두 가지 다른 재하 방법에 의한 두가지 다른 공식에 실험 데이타를 넣어서 이원 연립방정식을 풀어서 휨 剛度 D와 내부재료의 전단 탄성계수 Gc를 계산하는 문제는 시험 데이타의 변화 때문에 실현화 될 수는 없었다.
5. 부착면에서 생기는 미끄러짐과 수평전단 응력과의 관계를 결정하기 위해서는 앞으로의 시험이 필요할 것이다. 이 미끄러짐 현상을 감안하여 D와 Gc를 결정하기 위해서는 부착면이 완전 剛이라는 가정을 하지 안는 다른 공식을 사용해야 할 것이다.
6. 이 연구에 제시된 데이타는 시험에 사용된 샌드위치판들의 상대적인 剛度와 強度를 제시하고 안전측으로 사용한다면 설계 목적에 어떤 지침이 되리라고 생각한다.

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Ⅰ. Introduction

A structural sandwich is a layered construction formed by bonding two thin facings to a thick core. The basic design criteria are to space the strong, thin facings far enough apart with a thick core to assure that the construction will be stiff, to provide a core that is rigid and strong enough to hold the facings flat through a bonding medium such as an adhesive layer, and to provide a core of sufficient shearing resistance.

The basic principle of spaced facings was dis covered about 1820 by a Frenchman named Dulean and panels utilizing asbestos board skin with vegetable fiber board cores were used as early as World War I. During World War II the trend to more efficient use of labor and materials, particularly in aircraft, resulted in an increasing use of panels. However, the development or adaptation of new materials, the majority of which are plastics, has made an impact on the field of sandwich construction. An example of their pote ntial is the use of plastic foams in building construction (10).

The important types of sandwich construction are at present metal-faced, honeycomb-cored panels, plywood-faced, honeycomb-cored panels, plywood faces with balsa core, metal faces with balsa core, and both metal any plywood faces over various collular cores, some formed in advan ce, some formed in situ by various forming processes or by expansion of especially prepared plastic beads. Other combinations are obviously possible. Although sandwich panels were at first developed mainly for aircraft they are also Considered to be lightweight, high strength building components which can be used as walls, roofs, or floors. Their properties make them especially suitable for prefabricated building components.

Along with the improvement of the componet materials of structural sandwichc onstruction, many attempts to define and determine the design parameters of a panel as a structural member have been made. Development of mathematical, formulas for the computation of parameters defining the flexural behavior of a structural sandwich panel subjacted to a lateral load is an example.

The objective of this study is to compare the experimental method of determining the flexural behavior of structural sandwich panels with the computation from the theoretical formulas. A theoretical method developed by March and Smith (4) was followed to express the deflection, bending stress of the facings and shear stress of the core of the structural sandwich panel made of two different facing materials as well as of the same material in both facings. Simplified and more practical formulas were approximated from the relatively complicated equations derived by the theoretical method. Some other formulas derived by different methods were introduced to be compared with each other in some special cases. More than 40 panels of various combinations in component materials and thickness were tested. and the results were compared with the values computed by using the formulas introducted.

Ⅱ. Theoretical Formulas

Theories and experiments for flexural behavior of sandwich construction will be treated on the basis of a simply supportedand laterally loaded beam as shown in Fig. 1, in which the notations for dimension are found. In an attempt to get the factor of two different facing materials within a sandwich panel involvedin the mathematical expression for deflection, bending stress in the facings and shear stress in the core of the sandwich beam, the method that March and Smith (4) have developed was followed as given in the Appendix.

Maximum deflection, at the center of the span, of a sandwich beam with different facing materials is, from Eq. (A63) in the Appendix;

$$W=\frac{Pa^3}{48D}\left((1+\eta\frac{h^2}{a^2}\right) \qquad (1)$$

where η is given by Equation (A64) in the Appendix, D is given by Equation (A61) in the Appendix. P is the total load applied at the center of the beam and a and h are the dimensions of the beam shown in Fig. 1 when $a'=0$.

Since f_1 is relatively small in most practical cases, the last term in Eq. (A61) is negligible. Thus, D may be approximated as;

$$D=\frac{bE_1}{3\lambda_1}\{3q^2f_1+3qf_1^2+f_1^3+(1/n\alpha)(3p^2f_2+3pf_2^2+f_2^3)\} \quad (2)$$

where;

$$\lambda=(1-\mu_{xy}\mu_{yx})$$

Nemerical values of $1/\alpha_1 G_1, \beta_1/\alpha_1$ and $\rho_1\beta_c/\alpha_1$ are, in the normal situation, very small in comparison with the value of $1/\alpha_1 G_c$. It is, therefore, well justified that a good approximaiton of η can be made as;

$$\eta=\frac{2_c}{h^3}\ \frac{1}{\alpha_1 G_c}(2qf_1+f_2^2) \quad (3)$$

Also q given by Euqation (A45) in the Appendix can be justified to be approximated as;

$$q=\frac{f_2^2/nP-f_1^2+2cf_c/nP}{2(f_1+f_2/nP)} \quad (4)$$

in the case of $a'\neq 0$, Eq. (1) may be replaced by the form;

$$W=\frac{Pa}{16D}\left[\frac{a'^2}{2}+aa'+\frac{a^2}{3}\left(1+\eta\ \frac{h^2}{a^2}\right)\right] \quad (5)$$

If the material and thickness of both facings are the same, Eq. (2) can be reduced to;

$$D=\frac{bE_f}{12\lambda_f}(h^3-c^3) \quad (6)$$

where subscript f denotes the facing material. Eq. (3) becomes;

$$\eta=\frac{E_f}{2\lambda_f G_c}\ \frac{c}{h^3}(h^2-c^2) \quad (7)$$

For most practical purposes, simple for mulas for calculating deflection of a simply supported sandwich beam have been proposed (3);

$$W=K_b\frac{P_a^3}{D}+K_s\frac{P_a}{N} \quad (8)$$

where

$$D=\frac{E_f b(h^3-c^3)}{12} \quad (8a)$$

$$N=\frac{(h+c)b}{2}G_c$$

and K_b and K_s are constants determined by the beam loading.

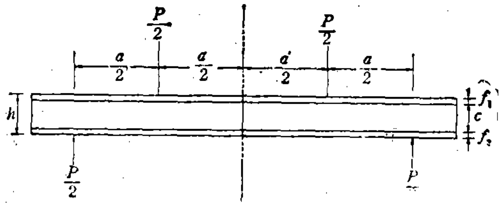

Fig 1. Simply Supported Sandwich Panel

Other formula for the central deflection of a simply supported sandwich beam subjected to a concentrated load at the centre, derived by Hoff and Mautner (2), are as follows;

(a) when pa/2<0.1

$$W=\frac{Pa^3}{48(2EI)_f} \quad (10)$$

(b) when pa/2>100

$$W=\frac{Pa^3}{48EI}+\frac{Pa}{4G_c hb}\ \frac{(EI)_1}{EI^-} \quad (11)$$

(c) when pa/2 approaches infinity,

$$W=\frac{Pa^3}{48EI} \quad (12)$$

In Equations (10), (11), and (12)

$$\left.\begin{aligned}2(EI)_f&=\frac{1}{6}f^3bE_f\\(EI)_1&=\frac{1}{2}fb(c+f)^2E_f\\EI&=(EI)_1+2(EI)_f\end{aligned}\right\} \quad (13)$$

$$\text{and } P=\sqrt{\frac{G_c h}{EI^*}} \quad (14)$$

$$\text{where } EI^*=\frac{(EI)_1(2EI)_f}{(EI)_1+2(EI)_f} \quad (15)$$

Bending stresses in the facings with different materials and thickness are expressed by the equations obtained by substituting appropriate values in Equation (A14) in the Appendix. This results in;

$$\sigma_1=-\frac{3Pa}{4b}\ \frac{q+f_1}{3q^2fl+3qf_1^2+f_1^3+(1/n\alpha)(3p^2f_2+3pf_2^2+f_2^3)} \quad (16)$$

$$\sigma_2=\frac{3Pa}{4n\alpha b}\ \frac{q+f_2}{3q^2f_1+3qf_1^2+f_1^3+(1/n\alpha)(3p^2f_2^2+3pf_2^2+f_2^3)} \quad (17)$$

where δ_1 and δ_2 are stresses at the center of the beam loaded by P, in the upper facing and lower facing, respectively.

For the beam having facings of the same material and thickness, Equations (16) and (17) may be reduced to:

$$\sigma_{1,2}=+\frac{3Pa}{2b}\ \frac{h}{h^3-c^3} \tag{18}$$

If the facings are sufficiently thinso that the cubes of their thicknesses may neglected, then Equation (18) can be reduced to a simpler form

$$\sigma_{1,2}=\pm\frac{Pa}{2b}\ \frac{1}{f(h+c)} \tag{19}$$

In deriving the equation for calculating shear stress in the core, sutstuting the appropriate values in Equation (A13) in the Appendix gives.

$$\tau=-P_1g_1[z^2-q^2-(1/P_1)(2qf_1+f_1^2)] \tag{20}$$

Since ρ_1 (s^2-q^2) is negligible relative to $2qf_1+f_1^2$, Equation (20) may be simplified with sufficient accuracy. That is: $\tau=g_1(2qf_1+f_1^2)$ Substituting $g_1=P/4\alpha_1D$ gives the final form:

$$\tau=\frac{3Pf_1(2q+f_1)}{4b[3q^2f_1+3qf_1^2+(1/n\alpha)(3p^2f^2+3pf_1^2+f_1^3)]} \tag{21}$$

Assuming that f is sufficiently thin so that hc can be approximated as $(h+c)^{2}/_{4}$, Equation (21) may be reduced to:

$$\tau=\frac{P}{b(h+c)} \tag{22}$$

Ⅲ. Description of Apparatus and Experimental Procedure

The test sepcimens were fabricated by a commercial manufacturer for these tests. The specimens are representative of panels having a width of 4 feet and a length of any convenient magnitude. There were 42 specimens consisting of 17 different combinations of facing materials core materisls, core thicknesses and adhesives. Facing materials include plywood, aluminum, fiberglas, galvanized steel sheet, and Masonite Presdwood. Core materials are solid polyurethane foam, paper-honeycomb and paper-honeycomb with polyurethane foam. The paper-honeycomb with polyurethane foam, trade name "Urecomb", is a paper-honeycomb impregnated with polyurethane foam as shown in Fig. 2. Cross sections of typical sample panels are as shown in Fig. 3. The length and width of all specimens tested were 48 inches and 10 inches, respectively. In the sample names the abbreviations used stand for the material names as follows:

P=Plywood facing
AL=Aluminum facing
FC=Fiberglas facing
GS=Galvanized steel facing
M=Masonite presdwood facing
SU=Solid polyurethane foam core
UC=Urecomb core
PC=Paper ihoneycomb core
(R)=Sp:cial rigid adhesive

Fig 2. Urecomb Core

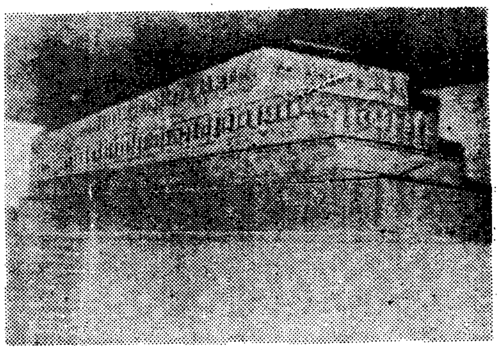

Fig 3. Typical Cross Section of Test Specimens

A testing machine, a model LW Dillon Tester with a 40″ daylight opening, was equipped with loading fittings for a benging test. Round steel pipes having a diameter of $1\frac{7}{8}$ inches were used in loading. The testing machine applies load at a uniform strain rate by means of an electric motor with speed control. A general view of the testing apparatus is shown in Fig. 4.

The midspan displacement of the test section is measured by means of a linear variable differential transformer (LVDT). The model chosen was a Schaevitz 1,000 HR with a±1,000 linear range. The transformer was rigidl mounted on the frame of the testing machine, and the coressemeiy was clamped to the driving plate ofthe testing machine when a midspan load test was made. When a quarterpoint load test was being made the core was fixed directly on the conterof the panel tested. The LVDT arrangement can be seen in Figs. 4(a) and 4(b). A Schaevitz carrer amplifier demodulator system (CAS-2,500), compatible with the LVDT, was used to provide an AC exciation to the primary transformer coils. The AC output from the transducer's secondary coil is returned to the carrier module, where it undergoes amplification and demodulation togive asmooth DC signa.

A10,000 lb Dillions train gage dynamometer was used to measure continuous total load applied to a specimen. A Sanborn carrier preamplifier provided AC bridge excitation, and conditioned the output signal for subsequent readout.

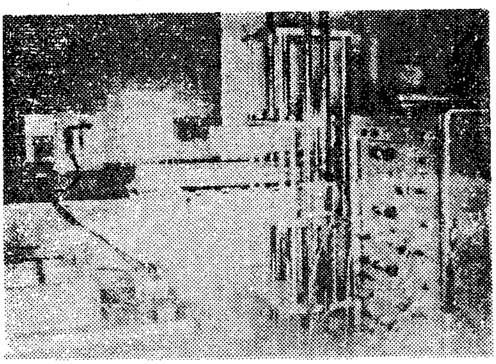

Fig 4. General Views of Testing Apparatus

Zero suppression was necassary to balance the bridge, and eliminate the high tare weight of the load fiittngs.

Visual readous of Signals from the CAS—2,500 and Sanborn carrier preamplifier was provided by an EAI Variplotter 1,000 E X-Y plotter.

The force-displacement testing procedure was in accordance with ASTM Standard(C393-62). Three basic tests were conducted on each test specimen. First, small loads were applied at the midpoint and outer quarter-points. Care was taken during each of these tests not to apply large loads which would cause yielding. Each of these tests were replicated several times turning the specimens over, regardless of whether the specimen was made of diff erent facing material. Finally, a single test was conducted with the panel loaded at the midpoint until failure. In the case of panels with different facing materials, the facings of aluminum, fiberglas or galvanized steel were keptup in the final test. The loading speed for all of the test was 0.2 in/min.

Ⅳ. Results and Discussion

A typical load/deformation diagram of a specimen tested to failure is shown in Fig. 5. Note that the load/deformation diagram is essentially linear for loads smaller than the failure load. However, it was noted that some samples which were significantly warped and were therefore not uniformly loaded initially did not produce linear load/deformation diagrams until enough load had been applied to remove initial warping deformations.

In the presentation of data and all results, the numbers have computed on the basis of a sample width of 12 inches for the convenience of a one foot module for design calculations.

Slopes P_1/w_1 and P_2/w_2, yield load P_1 yld and maximum load P_{1max} are presented in Table 3. The slopes P_1/w_1 and P_2/w_2 were taken from the linear portions of the load/defornation diagrams. Subscripts 1 and 2 in P_1, P_2, w_1 and w_2 denote the midspan load test and outer quarter-point load test, respectively. The yield load, P_1 yld, was determined as that load which occurs whe load/deformation has departed from the line by a deformation of 0.5 per cent of the span length. The value 0.5 percent was chosen as the minimum offset which consistently gives a well difined yield point. This is illustrated in the typical load/deformation diagram as shown

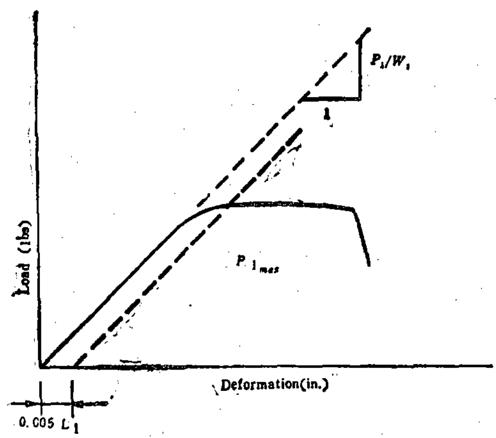

Fig 5. Typical load/deformation diagram for midpoint loading to failure

in Fig 5. The maximum load, P_{1max}, was takenfrom the peak point of the load/deformation diagram. The slopes P_1/w_1 and P_2/w_2 represent the average of the replicates. $P_{1\,yld}$ and P_{1max} are single values. These data for all tests are shown in Table 3. Blanks indicate that no data was taken.

Modes of falilure were observed and are presneted in the last column of Table 3. Letters *A*, *B*, *C*, *D*, *E* and *F* are used to denote: the limit of the apparatus, glueline slip, buckling on the top facing, local wrinkling of the facing, shearing rupture in the core, and bending failure of the facing, respectively.

The flexural stiffnesses, *D*, computed by Equation (2) are given in Table 4. Elastic constans of the component materials are taken from the references (5), (6), (13) and (16). The sources of information on the elastic constants are indicated in the table. The values of λ in Equation (2) were calculated from available information on Poisson's ratio whichin Table 5.

The modulus of rigidity of the core, G_c, is determined by utilizing the stiffness presented in Table 4 and the observed load/deformation diagrams for both the midpoint and quarter-point loadings. Equation (3) is used with Equation (1) to determineG_c from midpoint loadings and with Equation (5) to determine G_c from quarter-point loadings for each sample. The results of these computations are presented in Table 6.

The values of G_c given in Table 6 are presented graphically in Figs. 6 and 7. In these figures, the G_c values obtained from midpoint tests and quarter-point tests are separately indicated for each combination of specimens.

Table 1. Bening Test Data (Based on 12 inch width)

Sample name	P_1/w_1 lb/in	P/w_2 lb/in	P_{1yld} lb	P_{1max}	Mode of failure
Solid Urethane Core					
PSUAL—1	720	830	—	—	—
PSUAL—2	430	720	156	252	C
PSUFG—1	310	540	120	216	C
PSUFG—2	360	560	168	312	C
PSUGS—1	380	440	216	312	D
PSUGS—2	640	960	228	232	D
MSUAL—1	560	—	—	—	—
MSUAL—2	370	960	360	—	A
PSUP—1	770	1,080	624	840	A
PSUP—2	600	1,140	540	828	B
PSUP—3	480	960	—	—	—
PSUP—4	420	720	408	468	B
PSUP—5	240	540	186	210	B
PSUP—6	360	700	180	198	B
FGSUFG—1	270	420	348	378	C
FGSUFG—2	225	390	324	[illegible]	C
FGSUFG—3	346	713	300	294	D
FGSUFG—4	431	780	416	416	D
Paper Honeycomb Core					
PPCP—1	600	1,320	96	144	B
PPCP—2	600	1,320	72	132	B