Cement and Concrete Composites 18 (1996) 429–436

0958-9465/95/$15.00

PII:S0958-9465(96)00035-2

Steel Strip Reinforced High-density Wood Shaving–cement Board Ribbed Roof Panel

Guangjing Xiong

Dept of Civil Engineering, Shantou University, Shantou, 515063 China

(Received 31 January 1996; accepted 27 June 1996)

Abstract

The shortcomings of plain wood shaving–cement board roof panel are pointed out. A method to reinforce ribbed roof panel with steel strip is proposed. The flexural behaviour of the reinforced members is presented based on experimental study. The calculated methods chosen for predicting moment capacity and deflection of the reinforced ribbed roof panel show a good agreement with test results. © 1997 Elsevier Science Limited

INTRODUCTION

High-density wood shaving–cement board is a type of thin-sheet product with unit weight from 11 to 14 kN/m^3. In this composite wood shavings (18~25 mm long, 4~6 mm wide and 0.2~0.5 mm thick) are used as both reinforcing and filling materials. According to the requirements of practical uses the wood shaving/cement ratio may vary between 0.33 and 0.5, the water/cement ration is about 0.6–0.7 and the use of admixtures (such as Na_2SiO_3, $CaCl_2$ and $Al_2(SO_4)_3+Ca(OH)_2$) varies between 3 and 8% of the mass of cement. The manufacturing process includes: (1) cutting wood waste or tree branches into slices; (2) mixing the constituents; (3) compacting (under pressure of 1 MPa to 3 MPa) and curing (under high-pressure steam of 80°C) for up to 6~8 h to produce a dense composite with an even surface; and (4) further curing for up to 14 days at indoor temperature. In general, low wood shaving/cement ratio, low water/cement ratio and high compacting pressure lead to a high strength of the board.[1–6]

Wood shaving–cement board is thought to be a kind of low cost and energy-efficient material which combines the advantages of cement with those of wood, such as water and fire resistance, good heat insulation, a high level of resistance to fungi and termites and easy working with normal tools. Wood shaving–cement board has been widely used in many countries for production of exterior and interior wall panels, ceilings, corrugated sheet roofing elements, fassias, closets and mobile houses.[1–6]

However, the tensile strength and elastic modulus of this material are relatively low. Adequate measures, therefore, should be undertaken when it is used for making flexural members. The objectives of this study are to (a) propose a method to reinforce the flexural member for a rational use of this material, (b) provide a clear understanding of the flexural behaviour of the reinforced members and (c) develop a method for designing the reinforced ribbed roof panel.

EVALUATION OF PLAIN WOOD SHAVING–CEMENT BOARD ROOF PANEL

Figure 1 (top) shows the conventional cross-section of the wood shaving–cement board roof panel. Due to the low modulus of elasticity and creep of the material, the depth of the panel has to be relatively high to obtain a certain stiffness. The load-carrying capacity of the roof panel is dictated by the tensile strength of its lower flange. Since the tensile failure mode of this kind of member is brittle (Fig. 1 (bottom)) and the tensile strength of this material is only about one-third of its compressive strength, the use of this kind of roof panel leads to a wasteful construction.

In order to solve the problems mentioned above the author puts forward the idea of steel strip reinforced ribbed wood shaving–cement board roof panel as shown in Fig. 2. The steel strip is intended to be glued to the bottom of the rib.

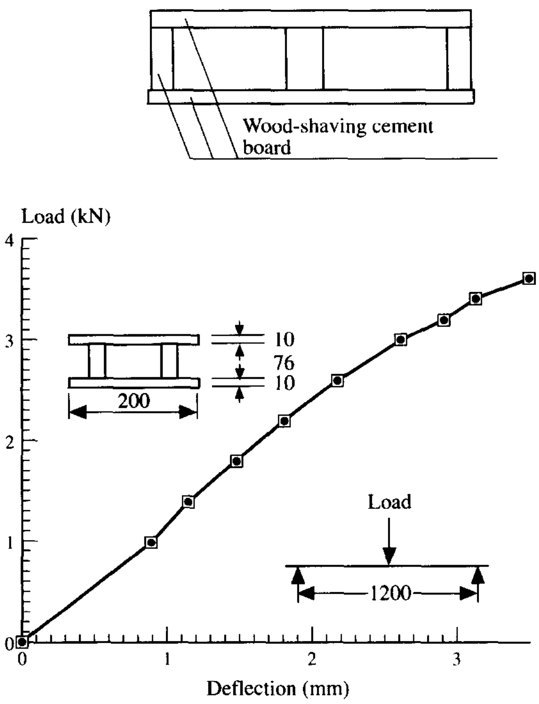

Fig. 1. (Top) conventional cross-section of wood shaving–cement board roof panel; (bottom) a typical load–deflection curve of plain wood shaving–cement flexural member tested by the author.

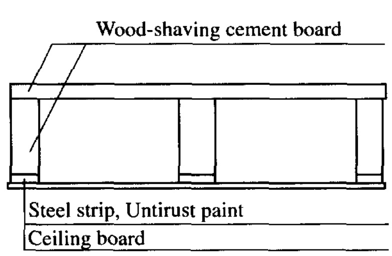

Fig. 2. Proposed cross-section of steel strip reinforced ribbed roof panel.

MATERIALS AND GLUING METHOD

Mechanical properties of the wood shaving–cement board used

In order to design the reinforced wood shaving–cement board flexural member, it is necessary to master the detailed mechanical properties of the wood shaving–cement board, such as bending strength and elastic modulus circling the *y*-axis (Fig. 3). Since the existing test specifications were not overall the Chinese national standard "Test Method of Physical and Mechanical Features of Wood" (GB 1927~1948), was used as a reference[7] for working out the testing methods for the measurement of these properties. Testing samples were drawn from the product of Beijing Dandian Brick Plant. The mixture proportions in the composite were 1:0.33:0.55 (blast furnace cement:wood shaving-:water) and the unit weight of the product was 13.78 kN/m^3.

The test results are listed in Table 1.

Properties of steel strips used

Steel strips with thickness of 1, 2 and 3 mm were used. The strength and elastic modulus of these steel strips are listed in Table 2.

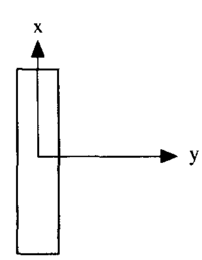

Fig. 3. Coordinate system for determining the mechanical behaviour of wood shaving–cement board.

Table 1. Testing data of mechanical properties of wood shaving–cement board

Mechanical properties	*Number of specimens*	*Average*	*COV (%)*
Bending strength circling *x*-axis R_{bx}	19	8.9 MPa	12.3
Bending elastic modulus circling *x*-axis	10	5494 MPa	16.0
Bending strenth circling *y*-axis R_{by}	9	6.9 MPa	9.9
Bending elastic modulus circling *y*-axis	9	5571 MPa	17.0
Tensile strength R_l	19	3.6 MPa	10.9
Tensile elastic modulus E_l	14	6837 MPa	9.5
Compression strength R_a	21	11.5 MPa	13.8
Compression elastic modulus E_a	21	6846 MPa	7.6
Poisson's ratio μ	14	0.223	19.2

Table 2. Testing data of mechanical properties of steel strips

Thickness (mm)	*Number of specimens*	*Mechanical properties*	*Average (MPa)*	*COV (%)*	*Remarks*
1	10	Yield strength R_s	241	10.3	Hot rolling
		Ultimate strength R_{su}	392	13.2	
		Elastic modulus E_s	200180	4.1	
2	8	Yield strength R_s	223	10.0	Cold rolling
		Ultimate strength R_{su}	345	12.7	
		Elastic modulus E_s	214394	8.1	
3	6	Yield strength R_s	204	8.1	Hot rolling
		Ultimate strength R_{su}	307	10.4	
		Elastic modulus E_s	196874	15.6	

Adhesive and gluing method for steel and wood shaving–cement board

The mixture of unsaturated polyester and silicon powder was chosen as the adhesive, and the gluing method was determined based on bond tests. Top and bottom surfaces of the wood shaving–cement board rib must be machined prior to gluing. The glue must be spread twice with an interval to allow a certain amount of

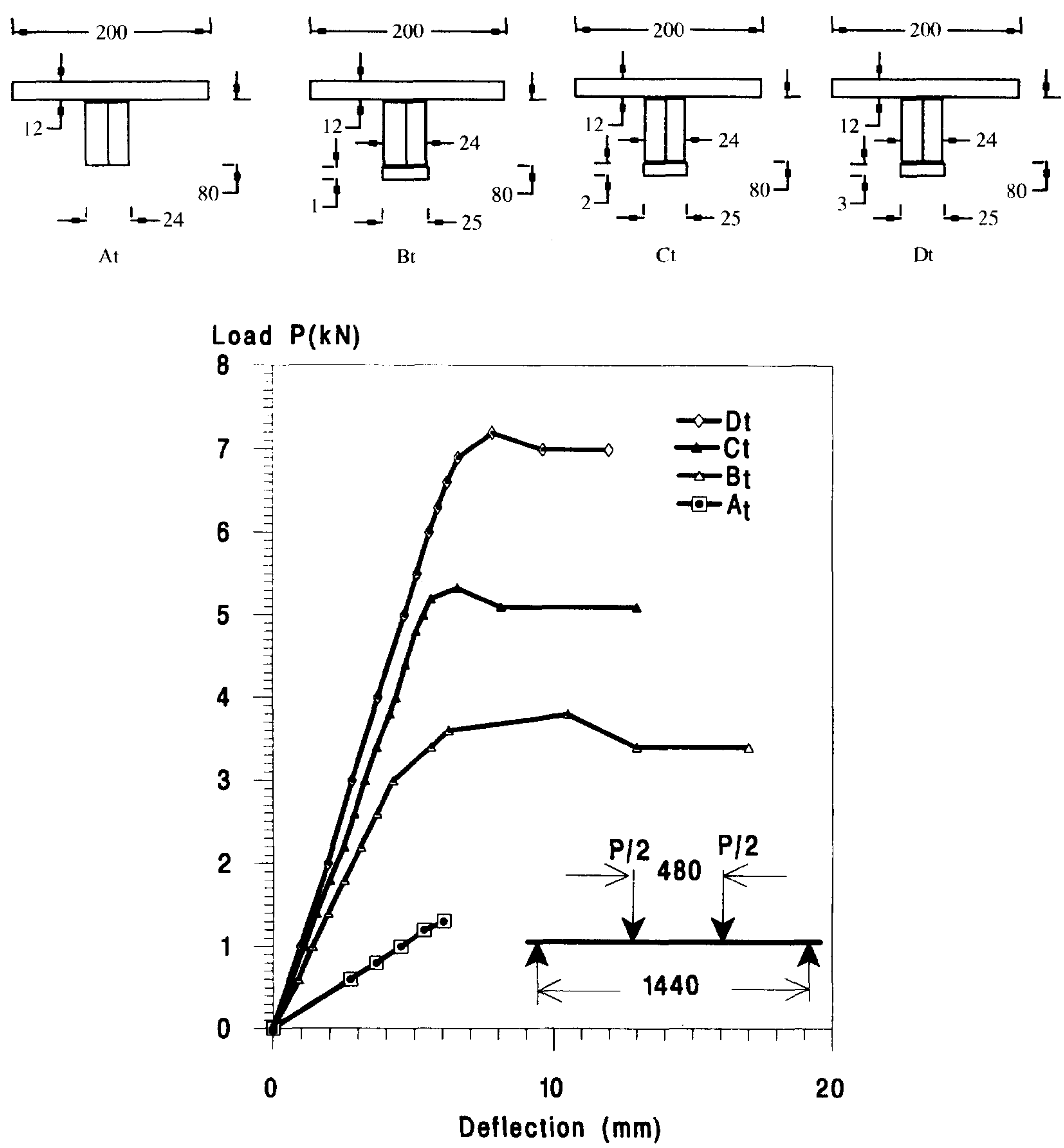

Fig. 4. Load–deflection curves of T-type beams.

glue to be absorbed by the surface of the rib. Adequate pressure is applied by screws. The glued members should be cured at indoor temperature for 3 days.

BEHAVIOUR OF T-SHAPE SPECIMEN UNDER FLEXURE

Specimen preparation

As an important step in the research program the relatively simple midsize T-shape specimens (Fig. 4) were designed and investigated first. According to their reinforcement ratios, the specimens were divided into four groups and each group contained six specimens. The effects of steel ratio on calculated elastic ultimate and stiffness for every group of specimens are listed in Table 3.

Behaviour under loading

The typical load–deflection curves for the four groups of specimens are shown in Fig. 4. The load–deflection curves for reinforced specimens show three distinct stages. The stress distributions at midspan cross-sections corresponding to the three stages are presented in Fig. 5. The behaviour of group C_t specimens with steel strip of 2 mm thickness is chosen as representative of reinforced members in the following discussion:

The elastic stage: Reinforcement can be assumed to be fully bonded with wood shaving–cement board, the distributions of stresses in the two phases are linear and the deflection is proportional to the load (Fig. 4). The end of this stage is indicated by the yield of the steel strip as shown in Fig. 5(Ia) and the load at this moment is defined as elastic ultimate. It should be noted that when the steel stress reaches yield strength the corresponding stress in the lower edge of the wood shaving–cement board rib is only 5.8 MPa. Because it is less than the ultimate bending strength R_{by} (R_{by} = 6.9 MPa—see Table 1), the crack does not occur.

The inelastic stage: The beginning of this stage is indicated by the occurrence of the plastic deformation in the steel strip and a slight decrease of the slope of the load–deflection curve. The stress in the wood shaving–cement board rib keeps increasing and one crack appears when the stress in the lower edge exceeds the ultimate bending strength R_{by}. Whilst the stress in the steel keeps a high value, that in the lower edge of the rib has to be zero at this cracked section. This causes shear stress concentration in glue line between steel and rib, resulting in debonding to progress from the cracked section towards the two supports as

Table 3. Effects of steel strips on the T-type members

Items	*Group of specimens*			
	At	Bt	Ct	Dt
Rate of the elastic ultimate load-carrying capacity	1	1.89	3.32	4.30
Rate of the stiffness	1	2.86	4.07	4.77
Ratio between compressive zone depth and cross-section depth (within elastic stage)	0.26	0.37	0.47	0.53

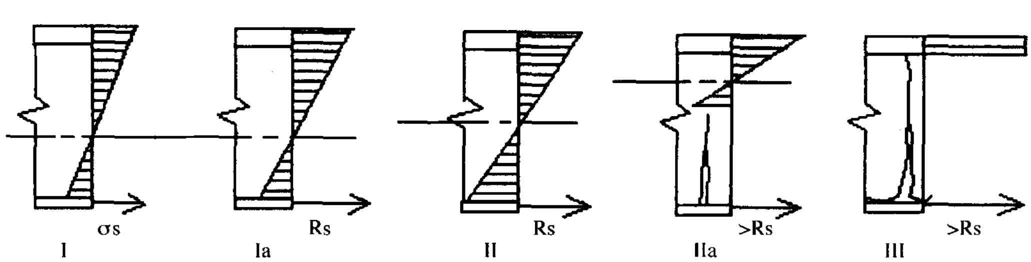

Fig. 5. Three stages of stress development in T-type specimen.

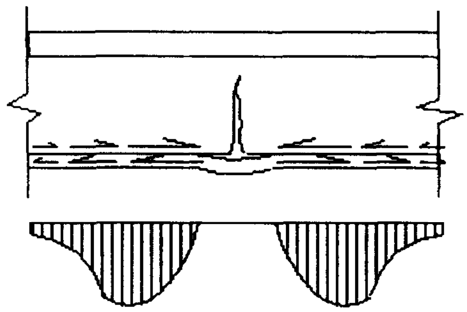

Fig. 6. Shear stress concentration in glue line.

shown in Fig. 6. The neutral axis rises gradually with the extension of the crack as shown in Fig. 5(IIa). The decrease of the slope of the load–deflection curve becomes more and more sharp due to the decrease of stiffness of the member caused by debonding and plastic deformation of steel (Fig. 4). When the crack of the rib extends to the upper boundary of the rib, the load–deflection curve drops down slightly. It should be noted that only one crack is observed in this stage.

Third stage: During this stage the load remains constant whilst the deflection increases significantly. No new cracks are observed in this stage. Because the existing crack runs through the whole height of the rib the moment due to applied load is resisted by the internal tension-compression couple consisted of steel strip and top flange only as shown in Fig. 5(III). By using the couple value, the average tensile stress in steel and the average compressive stress in flange can be predicted to be equal to 281 and 5.86 MPa, respectively. Evidence shows that the steel stress value is higher than the yield strength (223 MPa) and the stress value in flange is much lower than the compressive strength (11.5 MPa) of it. During this stage the debonding length stretches further and finally an excessive debonding length leads to the loss of load-carrying capacity of the member.

Discussion on effect of reinforcement and failure feature

Based on Table 3 and Fig. 4 it can be seen that the main advantages of steel strip reinforced wood shaving–cement board flexural members, as compared with the plain one, are to have higher load-carrying capacity, greater stiffness and plastic properties.

It is important to point out that the failure feature of the steel strip reinforced wood shaving–cement board member presented above is totally different from that of reinforced concrete. One of the main reasons is that the tensile strength of concrete is far less than that of the wood shaving–cement board and the elastic modulus of the former is much higher than that of the latter.

REINFORCED RIBBED ROOF PANEL

Design and calculation

Based on the research results presented above and according to the demand for roof panel, a cross-section of reinforced wood shaving–cement board ribbed roof panel is proposed, as shown in Fig. 7 (top): The reinforcement density of the panel is 1.5 kg/m^2. The cost of the panel is about \$1/m^2 lower than that of plain roof panel.

The load-carrying capacity of the roof panel is confined to the elastic ultimate.

The fundamental assumptions and calculating method of ribbed panel in elastic thin-slab

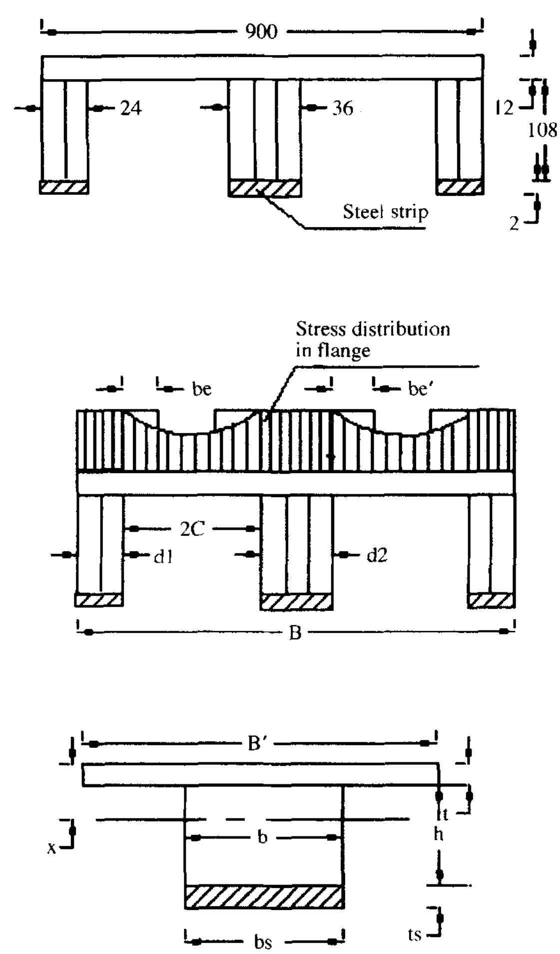

Fig. 7. (Top) cross-section of the roof panel; (middle) stress distribution in flange; (bottom) converted cross-section.

theory[8] are used for predicting stress and deflection of the roof panel. According to this method the distribution of compression stresses along the width of the flange is non-uniform, as shown in Fig. 7 (middle), and the distribution regularity is a function of the dimensions of the cross-section and the span. For practical engineering design, the flange B wide with non-uniform distribution of stresses can be converted into an equivalent flange B' wide with uniform distribution of stresses[8] as shown in Fig. 7 (bottom). The converted equivalent width B' is obtained by using the following equation

$$B' = 2d_1 + d_2 + 2b_e + 2b_e' \quad (1)$$

where: d_1 and d_2 are the widths of side ribs and middle rib; and b_e and b_e' are dimensions of converted distribution of stresses

$$b_e = l/2\pi[(\mathrm{sh}2c\pi/l + 2c\pi/l)/(\mathrm{ch}2c\pi/l + 1)] \quad (2)$$

$$b_e' = 2l/\pi\{(\mathrm{ch}2c\pi/l - 1)/[(3+\mu)\mathrm{sh}2c\pi/l - (1+\mu)2c\pi/l]\} \quad (3)$$

where: l—span of the panel; $2c$—clear width between ribs; μ—Poisson's ratio. When $c/l \to \infty$, $b_e = 0.1591$, $b_e' = 0.2051$. The location of the neutral axis is determined by the following equation

$$x = [n_1 B' t^2/2 + bh(h/2+t) + n_2 t_s b_s (h+t+t_s/2)]/[n_1 B' t + bh + n_2 t_s b_s] \quad (4)$$

where: $n_1 = E_c/E_{by}$, $n_2 = E_S/E_{by}$; E_c—compression elastic modulus of flange (MPa); E_{by}—bending elastic modulus of rib (MPa); E_s—elastic modulus of steel strip (MPa); t and B'—thickness and equivalent width of flange; h and b—depth and total width of ribs; t_s and b_s—thickness and total width of steel strips. The moment of inertia can be determined by the following equation:

$$I = n_1[(B't^3/12) + B't(x-t/2)^2] + [(bh^3/12) + bh(h/2+t-x)^2] + n_2 t_s b_s (h+t+t_s/2-x)^2 \quad (5)$$

The following three equations should be satisfied for strength requirement.

The compressive stress in top flange:

$$\sigma_c = n_1 M(x-t/2)/I \le [R_c] \quad (6)$$

The tensile stress in the lower edge of rib:

$$\sigma_{by} = M(h+t-x)/I \le [R_{by}] \quad (7)$$

The tensile stress in the steel strip:

$$\sigma_s = n_2 M(h+t-x+t_s/2)/I \le [R_S] \quad (8)$$

When the simple supported panel is loaded uniformly, the deflection should satisfy

$$f = 5ql^4/384E_{cy}I \le [f] \quad (9)$$

Loading test

The span of the roof panel is 2700 mm and simply supported. The roof panels A1 and A2 were loaded uniformly with iron pieces in steps of 1 kPa at intervals of 15 min and the deflection was measured by displacement metres. The load–deflection curve of panel A1 is shown in Fig. 8. The tested elastic ultimate load carrying capacity is between 6.3 and 6.8 kPa which is close to the theoretical value of 6.4 kPa. As in the case of T-shape specimens, only one crack was observed in each rib of the roof panel and the roof panel failed due to excessive extension of the debonding length.

A test on the roof panel A3 was performed under a testing rig consisting of a four point arrangement with a span of 2700 mm and a pure bending moment region of 900 mm. A downward jacking force was applied by a 20 kN hydraulic jack. Foil gauges were used to measure the strains, three ranks of strain gauges were arranged along the width of the flange and three ranks were arranged along the height of the ribs. Deflection was measured by displace-

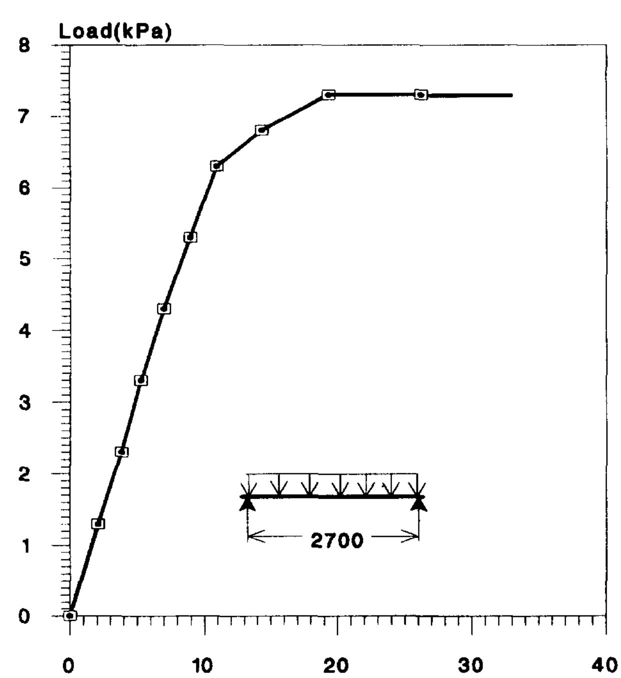

Fig. 8. Load–deflection curve of roof panel.

ment metres. The load was divided into six steps: 1.5, 4.5, 7.5, 10.5, 12 and 14 kN. A few minutes after the last step of the load was put on, the load went back from 14 to 12 kN automatically due to the plastic deformation of steel and the extension of debonding zone; this phenomenon repeated three times.

The distributions of strains in the flange and middle rib are shown in Figs 9 and 10, respectively. By using the test data in Fig. 9, the ratios of B'/B are calculated to be equal to 0.951–0.990, which are close to the theoretical value of 0.964 predicted by eqn (1). Test results (see Fig. 10) indicated that the steel strip yielded when the load value was about 12 kN, which was near to the predicted value of 12.36 kN obtained using eqn (8). The measured deflections of the three roof panels were 1.06, 4.96 and 9.76% higher than the theoretical prediction.

CONCLUSIONS

The main advantages of reinforced wood shaving–cement board flexural member, compared with the plain one, are higher load-carrying capacity, greater stiffness, greater plastic property, and lower cost.

The failure mechanism of reinforced wood shaving–cement board flexural member is distinct from that of reinforced concrete.

Reinforced wood shaving–cement board ribbed roof panel can be analyzed according to the method for ribbed plate in elastic thin-slab theory.

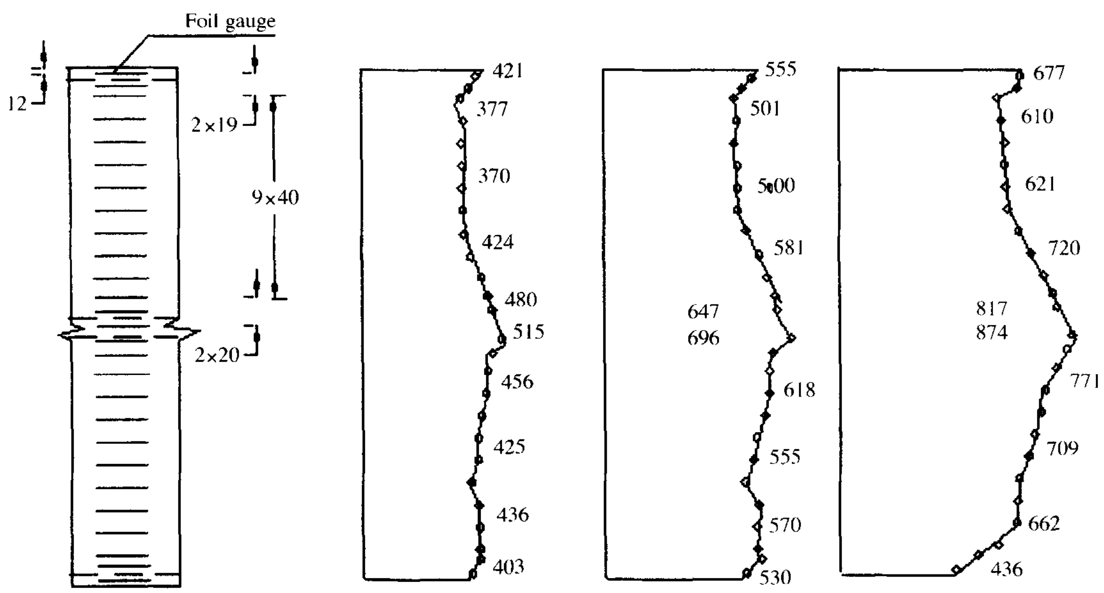

Fig. 9. Distribution of strains in flange of roof panel A_3.

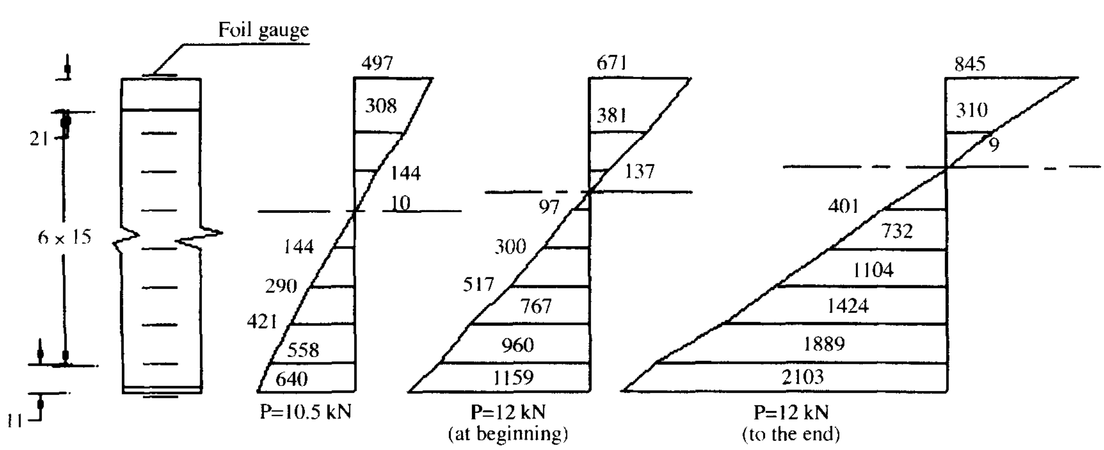

Fig. 10. Distribution of strains in middle rib of roof panel A_3.

REFERENCES

1. Sarja, A., Wood fibre reinforced concrete. In *Natural Fibre Reinforced Cement and Concrete*, UK, 1988, pp. 63–91.
2. Soroushian, P., Shah, Z., Won, J.-P. & Hsu, J. W., Durability and moisture sensitivity of recycled wast-paper–fibre cement composites. *Cement & Concrete Composites*, **2** (1994) 115–128.
3. Coutts, R. S. P. & Kightly, P., Bonding in wood fiber–cement composites. *J. of Materials Science*, **19** (1984) 3355–3359.
4. Soroushian, P., Shah, Z. & Won, J.-P., Optimization of wastepaper fibre–cement composites. *ACI Materials J.*, **92** (1995) 82–142.
5. Zhou, X., Production, properties and applications of wood shaving–cement board. *Products of Cement & Concrete*, **6** (1992) 40–44.
6. Tu, P., Discussion on production of wood shaving–cement board. In *Global Building Materials of Modern times and Future*, China, 1995, pp. 126–130.
7. GB1927-1948, Test method of physical and mechanical features of wood. Beijing, China, 1980.
8. Heins, C. P., *Applied Plate Theory for the Engineer*, USA, 1982.