Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 12 (1984)

Artikel: Composite timber and concrete components for walls

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DOI: https://doi.org/10.5169/seals-12143

Composite Timber and Concrete Components for Walls

Parois mixtes bois / béton

Verbundbauteile aus Beton und Holz für Wände

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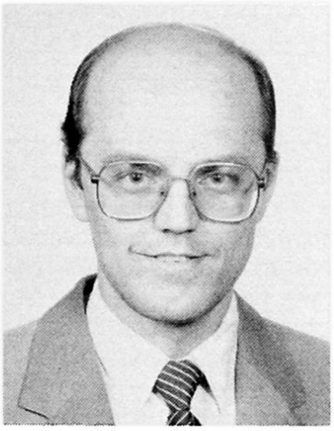


SUMMARY
Composite components often form technically and economically optimum structures. Composite concrete and timber components are often used in buildings and bridge construction. A composite concrete and timber component for walls has been developed. The component is a combined foundation and wall element and has nailplates as shear connectors. The component is mainly used in farm and industrial buildings. The behaviour and capacity of these components with incomplete interaction have been studied. The design and the way of erection of the component are described. Design procedures for service and ultimate loads are also presented.

RESUME
Les structures mixtes fournissent souvent d'excellentes solutions, en particulier celles composées de bois et de béton dans la construction de bâtiment et de ponts. C'est ainsi qu'une paroi mixte a été développée pour des bâtiments agricoles et industriels ainsi que pour leur fondation. Elle comprend des plaques de liaisons comme cloutage. Le projet et le montage sont décrits ainsi que les contrôles aux états limites.

ZUSAMMENFASSUNG
Eine Wandkonstruktion aus Beton und Holz wurde entwickelt. Der Bauteil besteht aus einem kombinierten Element, das Fundament und Wand umfasst. Die Schubverbindung erfolgt über Nagelplatten. Der Bauteil wird hauptsächlich bei Landwirtschafts- und Industriebauten verwendet. Das Verhalten und der Widerstand dieser Komponenten wurde untersucht. Die Montage der Wände wird beschrieben und Bemessungsverfahren für Gebrauchs- und Bruchzustand werden gegeben.

1. INTRODUCTION

Composite structural elements often form technically advanced and economically beneficial structures. Pre- and on-site fabricated composite timber-concrete elements have been successfully used in buildings as floors and walls, and in bridge construction [1,2] and [3,4]. Nails, bolts, glue or cutouts are usually used to develop shear connection in timber-concrete composites [5,6,7].

A new building element has been developed for application in industrial and agricultural builings [4]. The two important special features of the composite timber-concrete wall element are: (i) the element combines both the foundation and the wall elements; and (ii) the wall element is comprised of thin concrete plates attached to timber studs by means of nail-plate type shear connectors [8]. The structural details, the method of erection, and the design and behaviour of these elements are described in this paper.

2. DESCRIPTION OF THE COMPOSITE ELEMENT AND THE BUILDING SYSTEM

2.1 Details of the composite element

The composite wall element consists of concrete plates and two or more timber studs which are connected by nail-plates as shown in fig 1. The element is fabricated in five standard widths, the most commonly used width being 2400 mm. In addition to the standard widths, elements of any required non-standard width may also be manufactured. In agricultural buildings the concrete plate forms an impact resistant surface that can be easily cleaned. In addition to acting as a moisture barrier the concrete plate also serves to enhance the fire-resistance characteristics of the element. The timber studs form a bedding for the outer wall covering and reduce the risk of thermal bridges. The extention of the wall element to approximately 1.0 meters below ground surface level (the foundation part of the element) and the continuity of thermal insulation improve the stability and the thermal properties of the system. There are six holes at the bottom of the prefabricated wall element which permit the placement of reinforcement bars, allowing an in situ cast continuous footing. One of the timber studs extends above the element and the roof truss is anchored directly to the stud.

The placement of the composite element in a building is illustrated in fig. 2. The wall elements are attached to the floor slab by special anchors (reinforcement bars are placed in stirrups which are placed in the prefabricated elements prior to casting).

2.2 Erection of the composite elements

To erect the elements, the base layer of the concrete footing is first prepared, fig. 3. The elements are then lifted into position and adjacent elements are tied together by means of a nailed connection between the end studs of the units. A spacer block is used at the nailed connection to fill the gap between the end studs of adjacent units. The concrete is poured into the footing after the elements are in place, fig. 4. The footing thus obtained is integrated into the wall (fig. 2). After the concrete has cured and the soil is backfilled, the elements should be stable and the bracing is no longer needed. The roof trusses are attached to the wall elements after the concrete footing has set and after the special anchors have been fitted, the concrete floor slab is then poured at the desired elevation.

The erection procedure described above of an agricultural building designed to house 25 cows takes only two days to complete for three workers.

2.3 Special remarks

Even if water-tight concrete and jointing mastic are used in and between the wall elements, it is hard to prevent water from penetrating into the interior zone of the elment. For this reason the outer concrete plate just above the footing should be provided with ventilation holes in order to drain any possible penetrated water and ventilation channels should be arranged to aerate the elements below the ground level. This prevents the rotting of the timber studs and the loss of structural integrity of the element.

3. DESIGN PROCEDURES

3.1 General

The composite units are usually erected with the concrete plate exposed to the interior of the building, fig. 5. For the purpose of analysis the element is divided into two parts, the segment above the floor level (L) and the portion below the ground (ℓ). The segment above the slab is assumed to be fixed at the floor slab level and pin-connected to the roof trusses. The segment below the slab level is assumed to be fixed at the concrete footing and pin-connected to the concrete floor slab but subjected to a fixed end moment from the wall element above. If any window openings are placed in the upper part of the wall element, the bending stiffness of the wall can be assumed to be constant [9]. The axial compressive and tensile loads are assumed to act through the center of gravity of the concrete plate and the timber studs, respectively. (The shrinkage of the bottom chord of the roof truss and of the concrete plate will change the line of action of the axial loads).

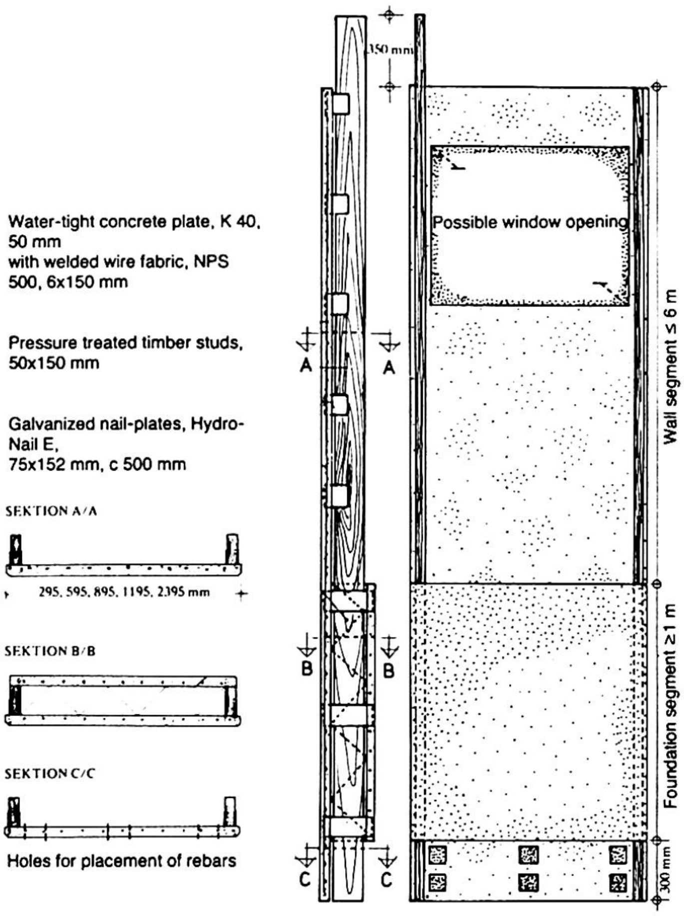


Fig. 1 *Details of the composite timber-concrete element with nail-plates*

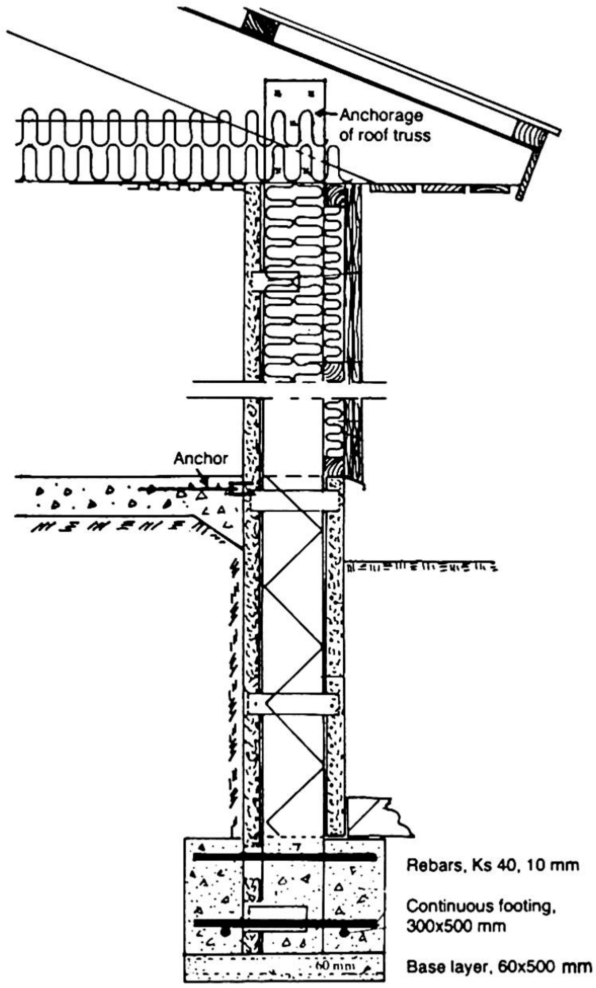


Fig. 2 *A wall section with the composite element*

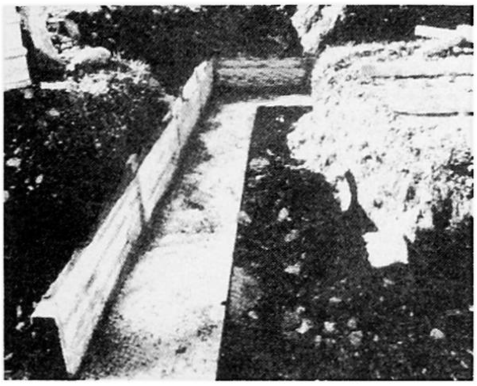
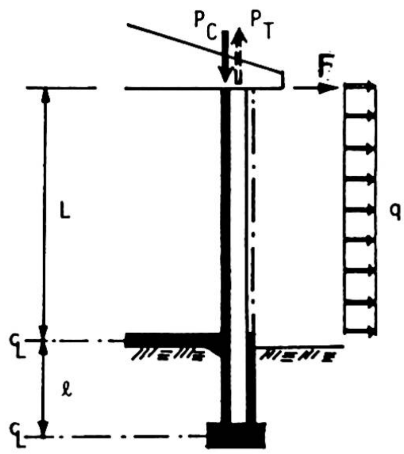


Fig. 3 *The base layer of the concrete footing*

Fig. 4 *The erected wall elements prior to casting of continuous footing*



P_C = Axial compression (center of concrete plate)

P_T = Axial tension (center of timber stud)

F = Stay force (support force)

q = Wind load

L = Theoretical length of wall segment

ℓ = Theoretical length of foundation segment

Fig. 5 *Wall and cross section of the composite timber-concrete element*

3.2 Analytical model for the composite elements

The behaviour of the concrete plate influences the overall behaviour of the composite element and depends upon whether the plate is in compression or in tension (cf. fig. 6 for definition) and also upon the rigidity of the shear connectors(slip modulus K [N/m²]) [9]. In the case of highly flexible shear connectors, the behaviour of the element will be similar to the behviour of composite elements with no composite action ($K \rightarrow 0$) and the reinforced concrete plate will crack in tension due to bending tensile stresses in both cases of the concrete plate in compression and in tension. In the case of very rigid shear connectors, the behaviour of the element will be similar to the behaviour of composite elements with full composite action ($K \rightarrow \infty$) and the reinforced concrete plate will crack only in the case of the concrete plate in tension. The composite element described here belongs to the former group (the composite element could however easily be made more rigid in shear by increasing the number of nail-plates).

The analytical model is therefore based on the assumption of a cracked reinforced concrete plate in both loading cases, fig. 6. The exterior load gives rise to the cross section moment M, which in turn causes interior axial forces (N_t, N_c) and moments (M_t, M_c) in the timber studs and the concrete plate, and also interior slip forces (T_n [N/m]) at the interface between the two submaterials. Since the concrete plate is relatively thin, it is assumed to have no bending (E_cI_c=0) but only axial stiffness (E_cA_c). For the sake of simplicity, the compressive stress (σ_c) is assumed to be evenly distributed over the cross section of the concrete plate and the tensile stress (σ_r) is assumed to be concentrated to the reinforcement, fig. 6. The true maximum compressive stress in the concrete would be twice this assumed uniform stress as approximately half the concrete thickness is in a cracked condition. The failure modes are then due to: (i) combined bending and axial tension/compression of the timber studs (f_t); (ii) shear or anchorage failure of the nail-plates (f_n);(iii) compression failure of the concrete plate (f_c); and (iv) tension failure of the steeel reinforcement (f_r). (In the case of rigid shear connectors, the only difference will be that the concrete plate in compression will be uncracked and thus have full axial and bending stiffnesses.)

3.3 Service load design

The composite elements are regarded as cantilevers subjected to five different kinds of loading as shown in fig. 7. The cantilevers represent the segment of the wall element above the floor slab level (with the length L) and the segment below (with the length ℓ), respectively, cf section 3.1. The real supporting and loading conditions at the upper end of the segments of the composite wall element can be represented by combining the different cases of loading. The first three and the last two cases refer to transversally and axially loaded elements, respectively. The force F is considered as positive when acting in the same direction as the evenly distributed load q and M_E is positive if it causes tension on the same side of the cantilever as that caused by the load q. By choosing the force F=—3qL/8 and by combining cases 1 and 2 a propped cantilever can be represented.

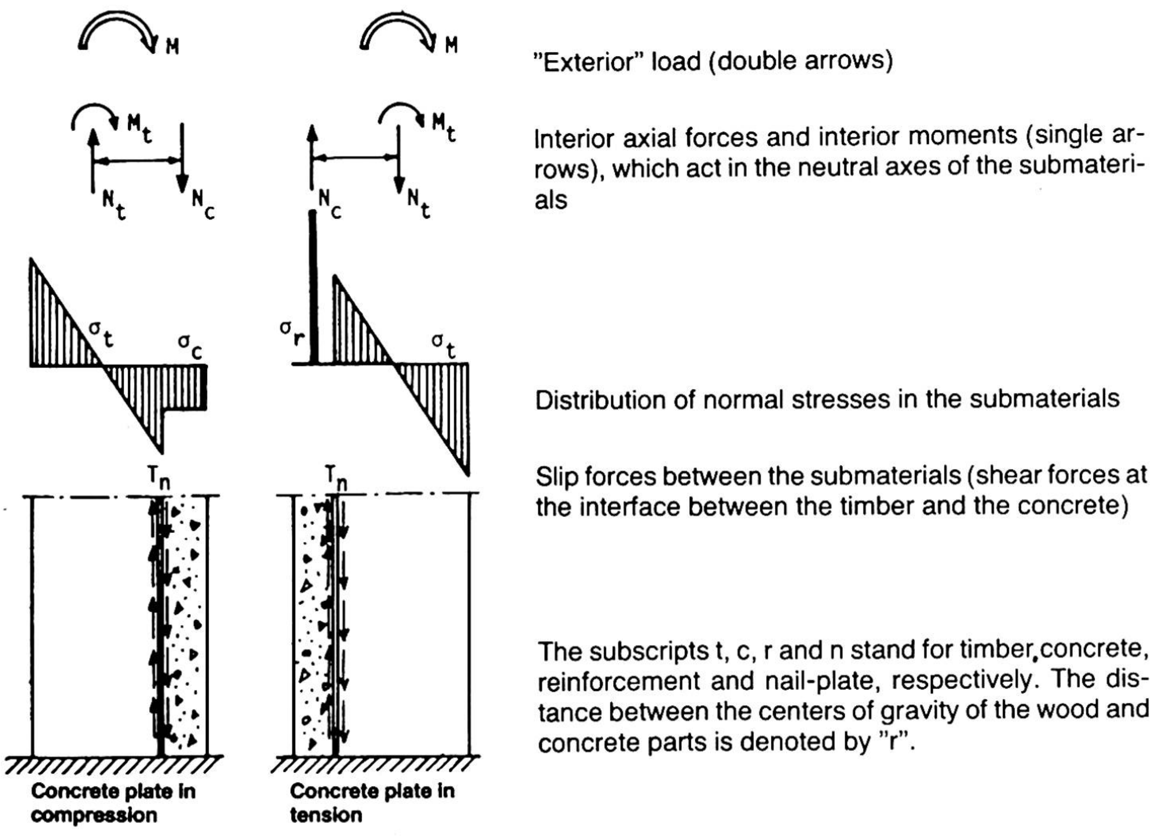


Fig. 6 *Definition of concrete plate in compression and concrete plate in tension. Analytical model for the composite element*

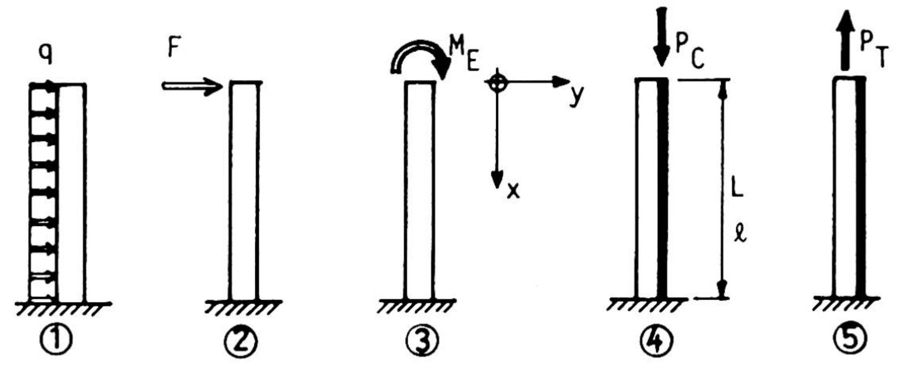
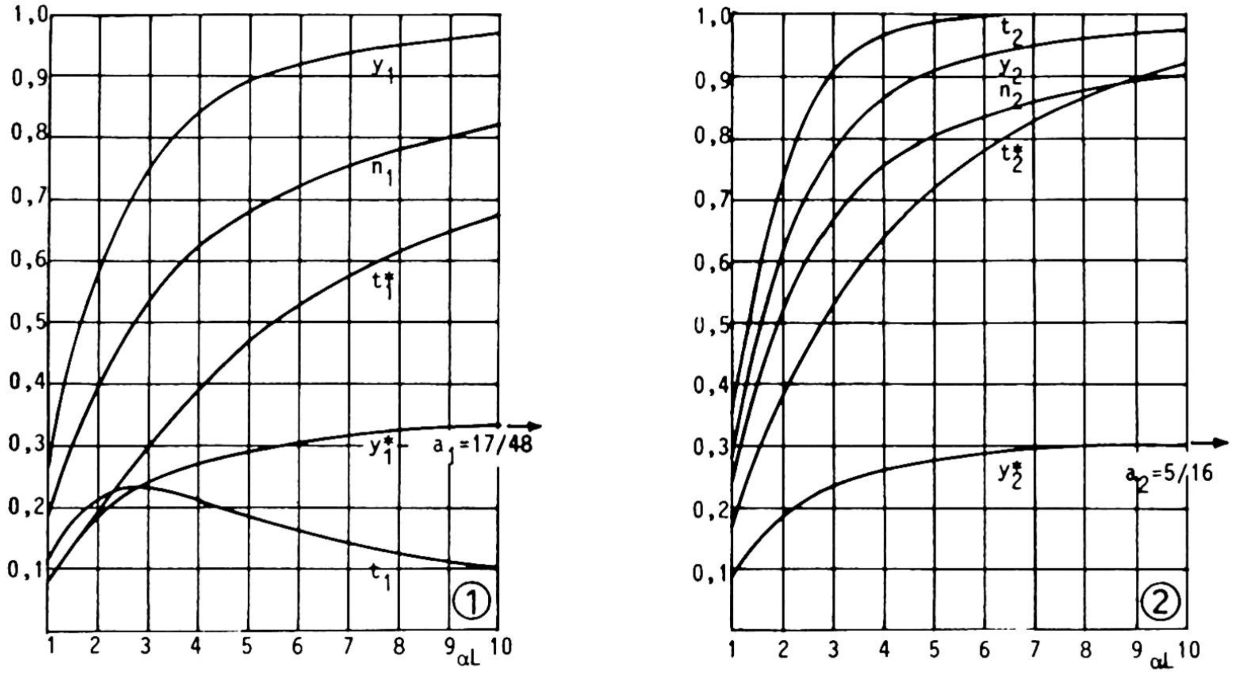
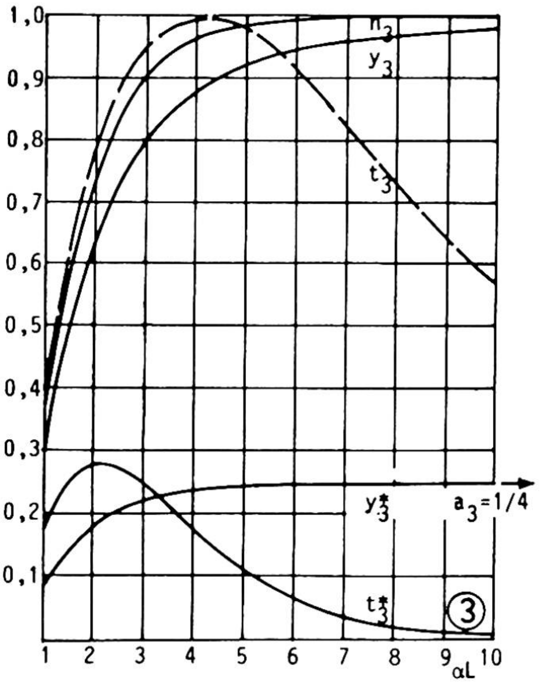


Fig.7 *Composite cantilevers subjected to three kinds of transversal loading and two kinds of axial loading*





Axial loading

$$N_{x=L} = n_3(1-\gamma/\alpha^2)P$$
$$M_{t,x=L} = N_{x=L}r$$
$$T_{n,x=0} = t_3(1-\gamma/\alpha^2)P/L$$
$$T_{n,x=3L/4} = t_3^*(1-\gamma/\alpha^2)P/L \qquad (8)\ \&\ (9)$$
$$y_{x=0} = y_3(1-\gamma/\alpha^2)PrL^2/EI_0$$
$$y_{x=L/2} = y_3^*(1-\gamma/\alpha^2)PrL^2/2EI_0$$

4 Axial compression

$$P = P_C\,;\ \gamma = \gamma_C\,;\ N_{x=L} = N_{t,\,x=L} = P_C - N_{c,x=L} \qquad (8)$$

5 Axial tension

$$P = P_T\,;\ \gamma = \gamma_T\,;\ N_{x=L} = N_{c,x=L} = P_T - N_{t,x=L} \qquad (9)$$

Fig. 8 *Functions and equations for axial forces, slip forces and deflections for the five different loading cases*

The theory of composite structures with incomplete interaction or interlayer slip is well established, e.g. [10]. For cantilevers as shown in fig. 7, the boundary conditions are: (i) N=P at the free end (x=0) and $\Delta u=0$ at the fixed end (x=L). (Note that for the segment of the wall element above the floor level, the condition $\Delta u=0$ is not fully correct since the wall element is continuous at the concrete floor level.) For the loading cases in fig. 7, the interior axial forces (N_t,N_c), moments (M_t ,M_c), slip forces (T_n), slip (Δu) and deflections (y) are generally given by, cf. [11].

$$N = (\beta/\alpha^2)\{[(M_{x=0} + M''_{x=0}/\alpha^2 - \alpha^2 P_{x=0}/\beta)\sinh(\alpha L) - (M'_{x=L}/\alpha + M'''_{x=L}/\alpha^3)]\sinh(\alpha x)\}\cosh(\alpha L) - (M_{x=0} + M''_{x=0}/\alpha^2 - \alpha^2 P_{x=0}/\beta)\cosh(\alpha x) + M + M''/\alpha^2\} \quad (1)$$

$$M_t = (E_tI_t/EI_0)(M - Nr) \quad ; \quad M_c=(E_cI_c/EI_0)(M - Nr) \quad (2)$$

$$T_n = N' \quad ; \quad \Delta u = T_n/K \quad (3)$$

$$y = (1-\beta r/\alpha^2)y_0 + (N - N_{x=L})r/\alpha^2 EI_0 \quad ; \quad y_0 = \text{deflection for } K\rightarrow 0 \quad (4)$$

where

$$\alpha^2 = K(1/E_tA_t + 1/E_cA_c + r^2/EI_0) \quad ; \quad \beta = Kr/EI_0 \quad (5)$$

$$\gamma_C = K(1/E_tA_t + r^2/EI_0) \quad ; \quad \gamma_T= K(1/E_cA_c + r^2/EI_0) \quad (6)$$

$$EI_0 = E_tI_t + E_cI_c \;; (K\rightarrow 0) \quad ; \quad EI_\infty = EI_0/(1-\beta r/\alpha^2 \;; (K\rightarrow\infty) \quad (7)$$

where prime denotes differentiation with respect to x, and EA, EI and K denote the axial, bending and shear connector stiffnesses, respectively. See also figs. 6 and 7. In the three cases of transversally loaded cantilevers we have (i)N_t=N_c=N and $P_{x=0}$=0; for the case of axial compression (ii) N_c=N, N_t=P_C–N, $M\rightarrow P_C$ and $\beta\rightarrow\gamma_C$ in eq. (1), and $M\rightarrow P_C r$ and $\beta r\rightarrow\gamma_C$ in eqs. (2) and (4); and in the case of axial tension (iii) N_t=N, N_c=P_T–N, $M\rightarrow P_T$ and $\beta\rightarrow\gamma_T$ in eq. (1) and $M\rightarrow P_T r$ and $\beta r\rightarrow\gamma_T$ in eqs (2) and (4). The maximum interior axial forces and moments always occur at x=L (except in the case of axial compression and tension). The maximum slip forces and deflections occur at locations which are dependant on the type of loading, the element properties and the end support conditions. For practical cases the slip forces and deflections should be evaluated at x=0, x≈L/2 and x≈3L/4. The maximum interior forces and moments, and deflections for the three types of transversal loading can then be written [9]:

$$N_{x=L} = n_i(\beta/\alpha^2)M_{x=L} \quad ; \quad M_{t,x=L} = [1 - n_i(\beta r/\alpha^2)]M_{x=L}$$

$$T_{n,x=0} = t_i(\beta/\alpha^2)M'_{x=L} \quad ; \quad T_{n,x=3L/4} = t_i^*(\beta/\alpha^2)M'_{x=L} \quad (8)$$

$$y_{x=0} =[1 - y_i(\beta r/\alpha^2)]y_{0,max} \quad ; \quad y_{x=L/2} = [a_i-y_i^*(\beta r/\alpha^2)]y_{0,max}$$

where the functions n_i, t_i, t_i^*, y_i, y_i^* and a_i for the three cases of transversal loading (i=1,2,3) are given in fig. 8 [12].Note that for the case of end moment (i=3) we must choose, $M'_{x=L}$=M_E/L. The one-dimensional engineered beam theory f composite structures used here will not always render correct slip forces at the boundaries as pointed out in [9] and [13]. To remedy this deficiency, a two-dimensional theory of elasticity has to be applied, cf. [14]. In the case where i=3 we have $T_{n,x=0}\rightarrow\infty$ for $K\rightarrow\infty$ according to the theory, which obviously is not correct.t_3, therefore, has been evaluated at a selected distance from the free end of the cantilever (x≈L/4) according to fig. 8. The maximum interior forces and moments and deflections for the two kinds of axial loading are given in eqs. (9) and (10) in fig. 8.

In combined loading cases, the sign conventions for moments, axial forces, slip forces and deflections are shown in fig. 9.

The normal stresses, slip forces and deflections are then given by

$$\sigma_t = N_t/A_t + M_t/W_t \le f_t^a \quad (11)$$

$$T_n \le f_n^a \quad (12)$$

$$\sigma_c = 2N_c/A_c \le f_c^a \quad ; \quad \text{Concrete plate in compression} \quad (13)$$

$$\sigma_r = N_c/A_r \le f_r^a \quad ; \quad \text{Concrete plate in tension} \quad (14)$$

$$y \le y_{limit} \text{ (e.g. L/90)} \quad ; \quad \text{Serviceablilty limit deflection} \quad (15)$$

where f^a denotes the allowable stress or force. In the case of combined bending and compression of the element, the internal moments (M_t) and deflections (y) should be multiplied by the following amplication factor [9]

$$v \simeq 1/(1\text{-}sP_C/P_{cr}) \quad (16)$$

where s=1,5-1,8 is the safety factor and where the critical load, P_{cr}, along with the buckling coefficients, λ, are given as

$$P_{cr} = P_{cr,\infty}/[1+(\beta r/\alpha^2)/(1\text{-}\beta r/\alpha^2)(1+\alpha^2/\lambda^2)] \quad (17)$$

$$\lambda = \begin{cases}\pi/2,1L & ; \text{ Cantilever case} \\ \pi/0,8L & ; \text{ Propped cantilever case}\end{cases} \quad (18)$$

3.4 Ultimate load design

The idealized load-slip curve for the nail-plates as shear connectors are given by fig. 10 [8]. As shown there are two stages of behaviour for the shear connectors:the elastic and the strain-hardening stages. Since the shear connectors control the overall response of the composite element, the element behaviour can be assumed to be similar to that of the shear connectors if the composite member components behave elastically. The transition from one stage to another starts at the most strained section and then spreads along the wall element. Using the safe assumption that when the most strained section reaches the strain-hardening stage, the whole element is said to have reached this stage, the formulae given in section 3.3 are still valid, the slip modulus $K = K_e \rightarrow K_{sh}$ being the only difference. Thus, the law of piecewise superposition can be applied. (No consideration is given here to repetative loading and deflection stability. Further, no load factor of safety is discussed). At ultimate load, the normal stresses, slip forces and deflections are then given by

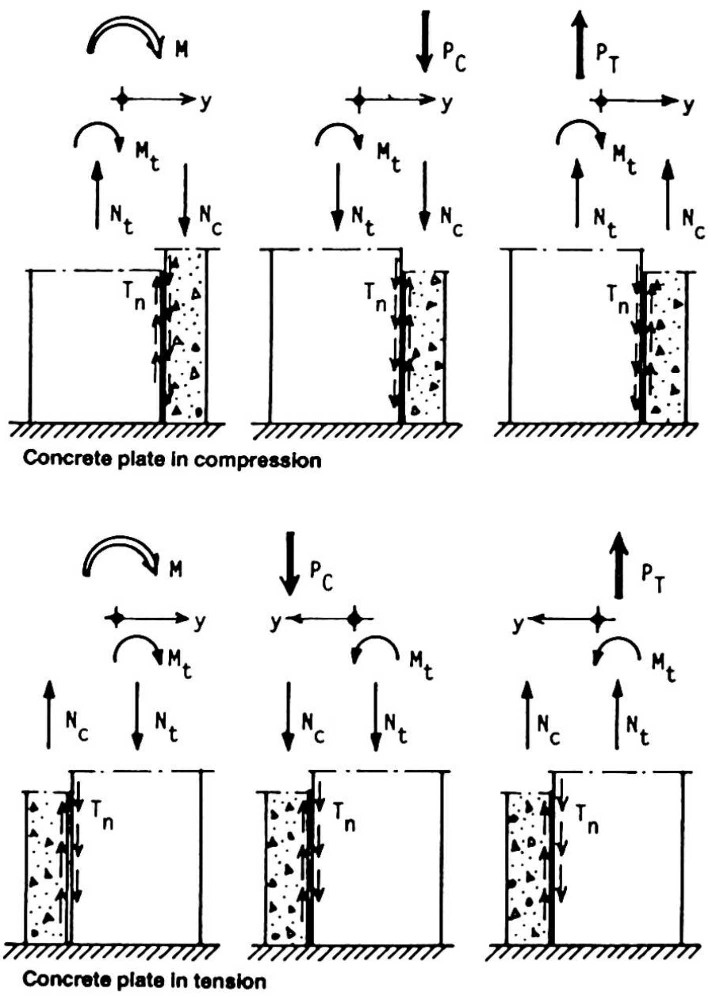


Fig. 9 *Sign conventions for axial forces, moments, slip forces and deflections in the composite elements*

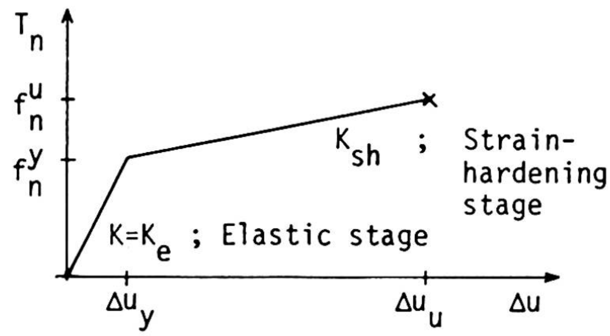


Fig. 10 *Idealized load-slipcurve for the nail-plates*

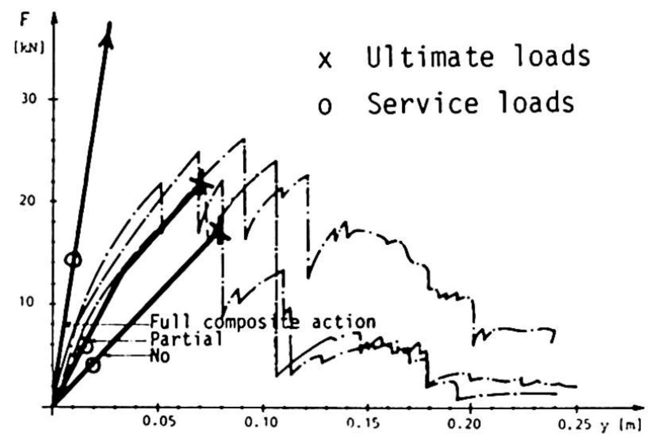


Fig. 11 *Test results for simply supported composite elements with concrete plate in compression compared to the proposed analytical model*

$$\sigma_t = N_t^e(Q_y) + [N_t^{sh}(Q-Q_y)]/A_t + [M_t^e(Q_y) + M_t^{sh}(Q-Q_y)]/W_t \leq f_t^u \tag{19}$$

$$T_n = T_n^e(Q_y) + T_n^{sh}(Q-Q_y) \leq f_n^u \tag{20}$$

$$\sigma_c = 2[N_c^e(Q_y) + N_c^{sh}(Q-Q_y)]/A_c \leq f_c^u \quad ; \quad \text{Concrete plate in compression} \tag{21}$$

$$\sigma_r = [N_c^e(Q_y) + N_c^{sh}(Q-Q_y)]/A_r \leq f_r^u \quad ; \quad \text{Concrete plate in tension} \tag{22}$$

$$y = y^e(Q_y) + y^{sh}(Q-Q_y) \leq y_u \quad ; \quad \text{Ultimate limit deflection} \tag{23}$$

where f^u denotes the ultimate stress or force, where $Q>Q_y$ is an arbitrary load and Q_y denotes the value of the load when the strain-hardening range is reached, i.e.

$$T_n(Q_y) = f_n^y \tag{24}$$

In a corresponding way the critical load in the strain-hardening range can be written (cf. Shanley's tangent modulus theory)

$$P_{cr} = P_{cr}^{sh} \tag{25}$$

3.5 Experimental verification

In order to verify the analytical method discribed above some tests on simply supported composite elements loaded at midspan were carried out [9] and one of the results is shown in fig. 11. The calculated values for service loads (eqs. 11-15) and for ultimate loads (eqs. 19-23) in the cases of full, partial and no composite action are also given in the figure. In all cases the determining failure mode was in the bending of the timber studs. It is evident from the figure that agreement is good.

REFERENCES

1. COOK, J.P.: *Composite Construction Methods.* John Wiley & Sons, 330 pp, New York 1977
2. SABNIS, G.M.: *Handbook of Composite Construction Engineering.* Van Nostrand Reinhold Company, 380 pp, New York 1979
3. PETERZÉN, S.: *EW Element - Concrete and Timber in Composite Action (in Swedish).* Swedish Journal of Building Art, No 1, pp 31-32, 1979
4. GIRHAMMAR, U.A.: *Rabo Foundation and Wall Element (in Swedish).* University of Luleå, Div of Struct Eng, Report 78:12, 16 pp, Luleå 1978
5. UNNIKRISHNA PILLAI, S. et. al.: *Nail Shear Connectors in Timber-Concrete Composites.* Journal Inst Eng (India) Civ Eng Div, Vol 58, No 1, pp 34-39, July 1977
6. PINCUS, G.: *Bonded Wood-Concrete T-Beams.* Proc ASCE, Journal Struct Div, Vol 95, No ST 10, pp 2265-2279, Oct 1969
7. DEGERMAN, T.: *Building Element Composed of Concrete and Timber - An Investigation of Different Types of Connections (in Swedish).* Lund Institute of Technology, Div of Struct Eng, Report TVBK-3012, 104 pp, Lund 1981
8. GIRHAMMAR, U.A.: *Nail-Plates as Shear Coonnectors in Composite Timber and Concrete Structures.* IABSE 12th Coongress, Vancouver, Final Report, Sept 1984
9. GIRHAMMAR, U.A.: *Rabo Wall Element - A Theoretical and Experimental Study of a Composite Element of Timber and Concrete (in Swedish).* University of Luleå, Div of Struct Eng, Research Report TULEA 1980:30, 286 pp, Luleå 1980
10. GOODMAN, J.R.: *Layered Wood Systems with Interlayer Slip.* University of California, Dept of Civ Eng, Doctoral Dissertation, 192 pp, Berkeley 1967
11. GIRHAMMAR, U.A.: *Composite Structures in Wood (in Swedish).* University of Luleå, Div of Struct Eng, Research Report TULEA 1983:43, 38 pp, Luleå 1983
12. GIRHAMMAR, U.A.: *Rabo Wall Element - Design Instructions and Documents of Standard Approval (in Swedish).* University of Luleå, Div of Struct Eng, Report 1980:11, 65 pp, Luleå 1980
13. SZALAI, J.: *Ermittlung der Verformung einseitig furnierter Platten infolge Feuchteänderung mit den Methoden der Festigkeitslehre.* Holztechnologie 21(1980)4, S. 221-226
14. CHEN, D. and CHENG, S.: *An Analysis of Adhesive-Bonded Single-Lap Joints.* ASME, Journal of Applied Mechanics, Vol 50, pp 109-115, March 1983