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Autor: Trinchero, Paolo E. / Kemp, Alan R.

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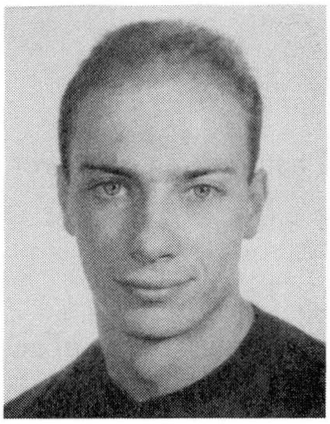
Serviceability Requirements for Composite Beams

Exigences d'aptitude au service des poutres mixtes

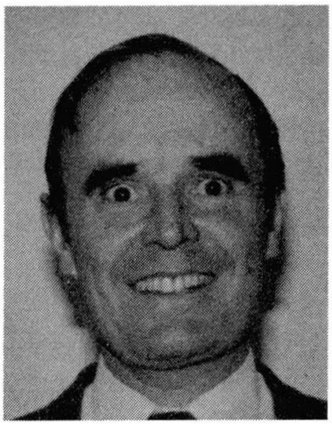
Gebrauchstauglichkeitsanforderungen an Verbundträger

Paolo E. TRINCHERO
Research Student
Univ. of the Witwatersrand
Johannesburg, South Africa

Alan R. KEMP
Prof. of Civil Eng.
Univ. of the Witwatersrand
Johannesburg, South Africa



Paolo E. Trinchero, 23, has a BSc from the University of the Witwatersrand and is currently a research student there.



Alan R. Kemp, born 1940, got his BSc and MSc at the University of the Witwatersrand and his PhD from Cambrige University. He was group consulting engineer of Dorman Long (Africa) and Manufacturing Manager of Dorbyl rolling stock before taking the Chair of structural Engineering, University of the Witwatersrand.

SUMMARY

Comparisons are provided between observed serviceability deflections in two composite beams and predictions of the effects of yielding, shrinkage, residual stress and interface slip. The relative importance of these effects is discussed. A prediction of natural frequencies of one of the beams also correlates well with observed behaviour.

RESUME

Les auteurs comparent les flèches observées sur deux poutres mixtes sous charge de service avec les effets préalablement prévus pour l'écoulement plastique, le retrait, la contrainte résiduelle et le glissement dans la surface de contact. Ce faisant, ils analysent l'importance relative de ces influences. La fréquence propre pronostiquée pour l'une des deux poutres correspond bien au comportement observé.

ZUSAMMENFASSUNG

Die beobachtete Durchbiegung zweier Verbundträger unter Gebrauchslast wird mit den vorherberechneten Auswirkungen von Fliessen, Schwinden, Eigenspannungen und Gleiten in der Verbundfläche verglichen. Dabei wird die unterschiedliche Wichtigkeit dieser Einflüsse diskutiert. Die Vorhersage der Eigenfrequenzen eines der Balken stimmt gut mit dem beobachteten Verhalten überein.

1. INTRODUCTION

An analysis of international design codes [1] has indicated that criteria for serviceability differ more significantly than for ultimate load conditions.This particularly applies to the ratio of serviceability to ultimate load; whether elastic stress limits are required and how shrinkage, creep and partial shear connection should be considered.Residual rolling or welding stresses are generally ignored.

The primary objective of the two tests described in this paper was to assess the relative contribution to serviceability deflection of the following effects:
i) short term elastic deflections
ii) yielding of the extreme fibres
iii) residual stresses due to rolling
iv) shrinkage of concrete slab
v) interface slip due to partial shear connection
vi) repeated application of serviceability load
vii) creep under long term load of one beam.
In addition a comparison was made between theoretical and observed natural frequencies of one beam.

2. DESCRIPTION OF TESTS

Two beams were tested to investigate these effects, representing a scaled down version of an unpropped, simply-supported beam and composite slab (or the positive moment region of a continuous beam), as follows:

SF : Sagging (positive) moment (S), unpropped specimen on 6m span with full shear connection (F) and composite deck.
SP : Sagging, unpropped specimen on 6m span with partial shear connection (P) and composite deck.

A distributed 4-point loading was applied (Fig 1) to the composite section to represent the distributed imposed load.The total dead load was achieved through additional weights of 9.8kN hung from the plain steel section.Although unpropped beams would normally be precambered against dead load, it was decided not to precamber these beams because of the unknown strain distribution that would otherwise be induced in the steel section.

The shear connectors are 19mm studs that were welded through the trapezoidal deck.A full shear connection is provided in test SF and 5 studs provide a partial shear connection factor of about 0.5 in beam SP based on the Canadian code.

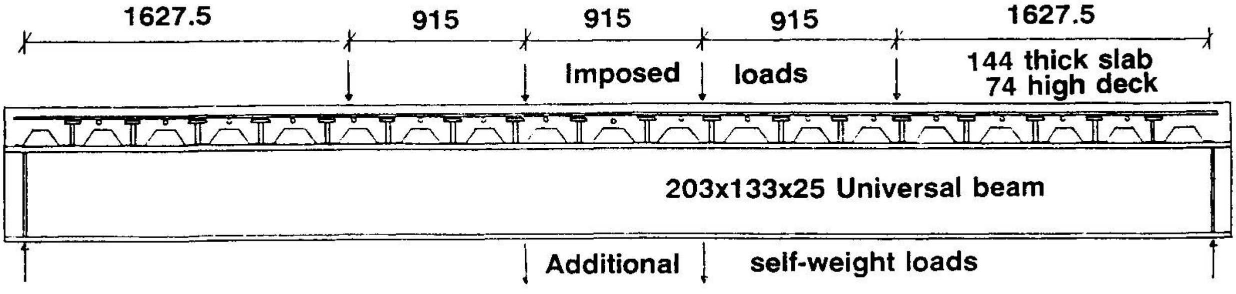
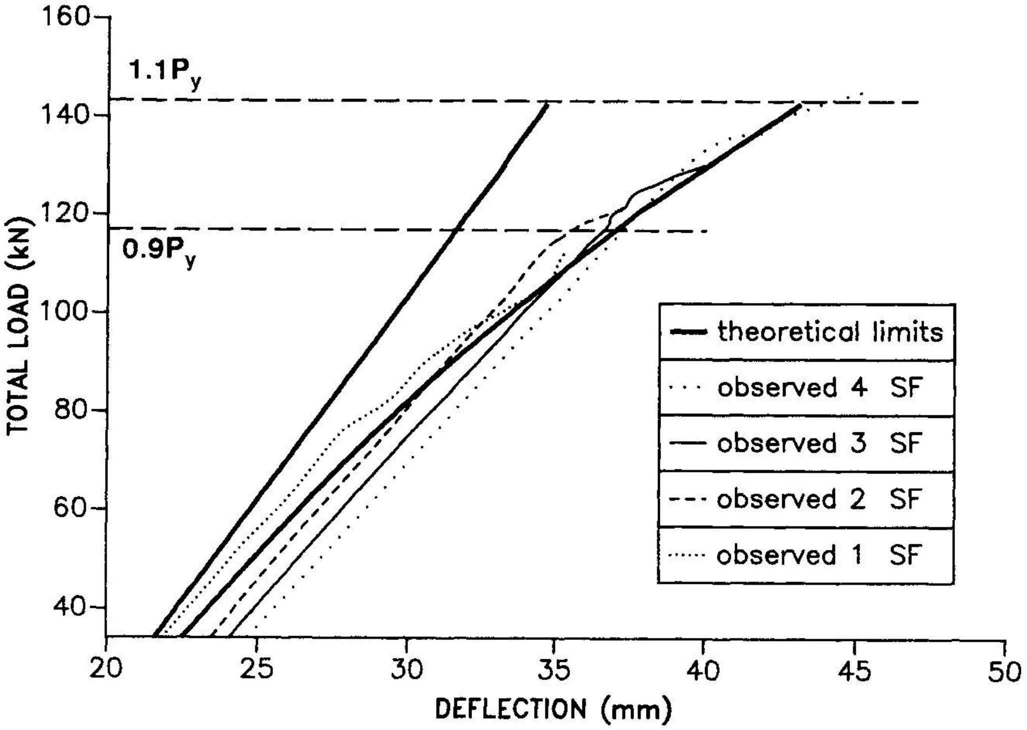
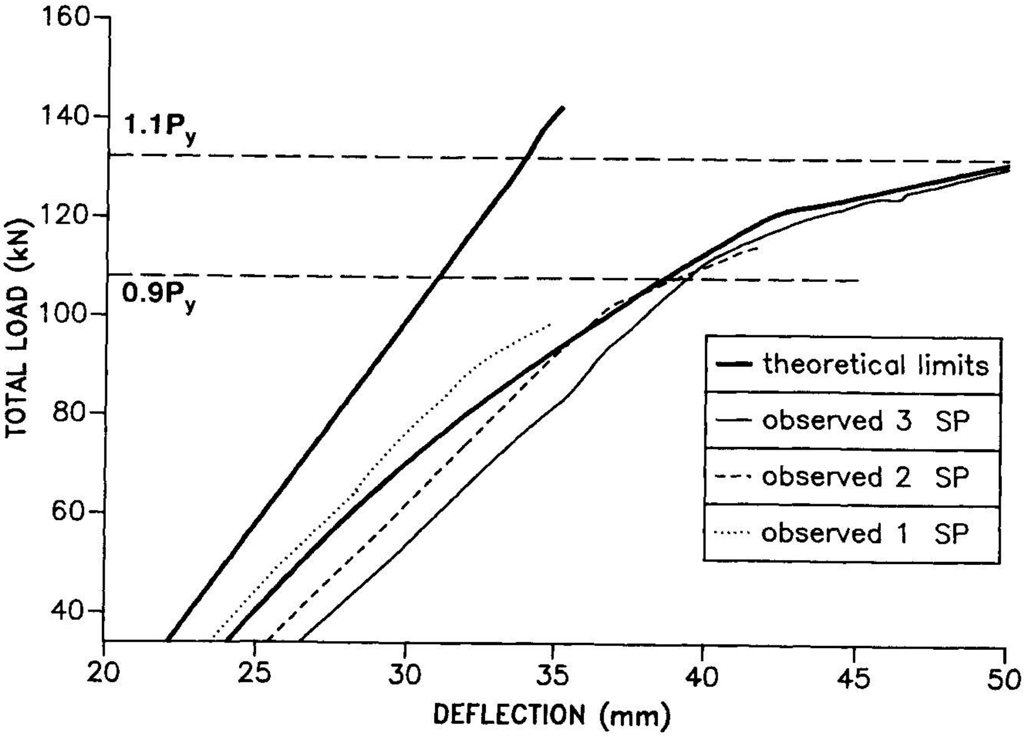


FIG.1.-Arrangement of Test Specimens SF and SP

In these tests the imposed load was applied over a number of load cycles to simulate repeated loading in the region of the load P_y that theoretically causes yielding of the extreme fibre. Although there were residual deflections on unloading, strain hardening ensured that on reloading a similar load-deflection line was followed after yielding (Figs. 2a and 2b).



(a) Full Shear Connection Specimen SF



(b) Partial Shear Connection Specimen SP

FIG.2.-Observed & Theoretical Load-Deflection Curves for SF & SP

When the serviceability testing was completed it was decided to monitor specimens SF and SP for further shrinkage.In simply supported composite construction, the effects of shrinkage and creep are generally additive and it is therefore important to consider their contribution when spans are long or beams are shallow.In a paper by Leon [2] it was found that in a typical simply supported composite beam design the shrinkage deflection can vary from five (propped construction) to fifteen times (unpropped construction) the creep deflection.

Creep is important when the ratio of dead to live load is large or when a significant portion of the live load is present for long periods of time.Leon[2] has suggested that 25 % of the live load can be considered to be the long term load.Approximately 20% of the live load was placed on specimen SP after 74 days and the creep effects were observed.Unfortunately due to time considerations the load was removed after 118 days which does not allow an accurate investigation of creep.Annoying floor motion induced by building occupancy is probably the most persistent floor serviceability problem encountered by designers.A series of dynamic tests were therefore performed on specimen SF to determine the natural frequency.

3. TEST RESULTS AND DISCUSSION

Theoretical stresses, strains and deflections for propped and unpropped beams (combining the effect of dead load on the plain steel section with imposed load on the composite section) were assessed at loads up to and beyond yield using a nonlinear, moment-curvature algorithm developed by Kemp [4].Shrinkage deflections were modelled using the model of Chien and Ritchie [3] and creep effects using a creep coefficient determined from specimen tests to obtain a long term concrete modulus.

The observed and theoretical relationships between total load and maximum deflection for tests SF and SP are shown in Figs. 2(a) and (b),starting at a total dead load applied to the unpropped plain steel section of 34.1 kN.The observed deflections under self-weight of the slab are about 19.3 and 20.1mm in tests SF and SP,to which should be added a deflection of 1.8mm for the self-weight of the steel beam and deck in these tests.Additional shrinkage deflections were 0.8 and 1.6mm prior to testing 12 and 19 days respectively after casting.The values of restrained shrinkage strain were included in the theoretical analyses.

The partial shear connection (SP) is modelled by introducing a slip strain at the interface that is proportional to the curvature and that when integrated over the half-span produces an interface slip deflection equal to that observed at the end of the beam.For the theoretical curves in Figs. 2(a) and 2(b) :the upper curve neglects residual stress, shrinkage and slip-strain and the lower curve includes the assumed residual stress patterns based on Young [5],shrinkage and slip-strains.It is apparent from these figures that the pairs of curves reflect the range of stiffness exhibited by the beams during loading and unloading cycles with surprising accuracy.

The test results are summarised in Table 1. and compared at load levels of 90% of the load required theoretically to cause yielding of the extreme fibre and 110% of this load.The following aspects are apparent from these results for unpropped composite beams:

1.Deflections due to shrinkage (associated with the measured values of restrained shrinkage in Table 1) and residual rolling stresses produce significant components of the serviceability deflections.The shrinkage effects may be predicted using Chien and Ritchie's model[3] and the effect of residual stress may be considered based on the distributions proposed by Young [5].

Table 1: Theoretical and Observed Deflections

Specimen		SF (Fig.2a)		SP (Fig.2b)	
Yield stress of flange MPa		317		312	
Yield stress of web MPa		329		336	
Cube strength MPa		32		37	
Mod. of elasticity GPa		27		29	
No. of 19mm studs 115mm high		14/half span		5/half span	
Deflection under self-weight (mm)	Observed	21.1		21.9	
	Theoretical	21.6		22.1	
Restrained shrinkage (ustrain)	Observed	55u @ 12 days		120u @ 19days	
Shrinkage deflection (mm)	Theoretical	0.9		2.0	
		0.8		1.6	
Live load level (kN)		$0.9P_y$	$1.1P_y$	$0.9P_y$	$1.1P_y$
Dead/live load ratio		0.41	0.31	0.46	0.35
Live load deflection effects (mm) Elastic	Theoretical	10.0	12.4	9.0	11.0
Yielding	Theoretical	-	0.7	-	0.9
Residual stress	Theoretical	3.4	6.5	2.4	4.8
Shrinkage	Theoretical	1.1	1.1	2.3	2.4
Connector slip	Theoretical	-	-	1.2	7.8
Total live + Dead load deflection (mm)	Theoretical	37.0	43.2	39.0	51.0
	Observed	35.5	44.7	37.2	51.3
Restrained shrinkage (ustrain)	Observed	307 u @ 89 days		270 u @ 74days	
Shrinkage deflection (mm)	Theoretical	5.2		4.5	
	Observed	4.5		4.2	
Ratio of Total Deflection @ $1.1p_y$/Deflection @ $0.9P_y$	Eqn (1)	1.22		1.26	
	Theoretical	1.17		1.31	
	Observed	1.26		1.38	
Creep deflection due to 18.84kN for 44 days (mm)	Theoretical	-		0.3	
	Observed	-		not significant	
Natural Frequencies (Hz)	Canadian Code	8.1		-	
	Observed	8.0		-	

2.Exceeding the elastic stress limit on the extreme fibre by a small amount ($1.10P_y$ in these tests)does not result in significant increases in deflection, but the interaction of this with residual stress and interface slip in beams with partial shear connection does cause an appreciable non-linear response.Serviceability limits of elastic stress, as in the Canadian and British composite codes, are not justified, particularly because they are considered in isolation of the level of deflection at which they occur [1].

3.The largest increases in deflection at serviceability occur due to interface slip at values of the partial shear connection factor of 0.5.This is not only caused by loss of flexural rigidity, but also by the associated stress distribution that causes premature yielding.Only the American design code refers separately to both of these effects.

4.Creep deflections are unlikely to be large in unpropped beams and may be assessed by using a reduced modulus of elasticity for the concrete based on the Effective Modulus or the Age Adjusted Modulus approach.Little difference was observed due to creep when one of the beams was subjected to an increment of 20 % of the serviceability live load over a prolonged period.

5.The assessment of natural frequency of beam SF using the formulation in the Canadian code provided a reasonably accurate prediction of the actual behaviour.

The composite Eurocode requires account to be taken of creep and shrinkage in the calculation of deflections.The effect of residual stress is neglected as in other codes and partial shear connection is only considered at a shear connection factor below 0.5 which is clearly an unconservative approach when compared to the test measurements.

The following proposal was developed [1] for modelling the non-linear amplification of deflection due to the interaction of shrinkage, yielding, residual stress and interface slip over the range of load from that producing an extreme fibre stress of 90 % of yield ($0.9P_y$) to $1{,}10P_y$:
"For composite beams in which the total serviceability load P_{serv} exceeds the minimum load P_d required to cause an elastic stress of either $0.9f_y$ in the steel beam or $0.6f_{cu}$ in the concrete (f_{cu} is the cube strength) or a moment of $0.75\ M_u$,the total serviceability deflection y_{serv} shall be calculated as follows:

$$y_{serv} = y_s(1-EI_s/EI_c) + y_{dc}(P_{serv}/P_d)^2 \qquad ......(1)$$

in which
y_s = elastic deflection due to load applied to plain steel section
EI_s = flexural rigidity of plain steel section
EI_c = flexural rigidity of composite section
y_{dc} = elastic deflection due to total load P_d (self-weight + imposed) applied to composite section and including shrinkage and interface slip
P_{serv} = total serviceability load in the range $P_d < P_{serv} < 1.225\ P_d$."

This empirical proposal reflecting the correct boundary conditions, compares favourably with results of experimental and theoretical analyses in the range of load from first yield at $0.9P_y$ to $1.10P_y$, as shown in Table 1.

4.CONCLUSIONS

The effects of shrinkage, residual stress and interfacel slip have a significant effect on the serviceability deflection of composite beams.Creep effects will commonly be significantly smaller.

Serviceability limits on levels of elastic stress irrespective of whether the deflections are critical at which these stresses occur, can lead to undue conservatism.

The current procedures for determining the natural frequency of composite beams are accurate.

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