Blinding struts under long-term loading

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The term 'blinding' is used to describe the thin layer of unreinforced over-site concrete used to protect the base of excavations during construction. Blinding is not generally considered a structural element even though it clearly provides some temporary lateral support to the retaining walls of excavations. The authors have previously shown that enhanced blinding can be used to prop retaining walls in cut-and-cover excavations during construction prior to the completion of the base slab. This paper describes a series of laboratory tests carried out to investigate the effect of concrete creep on the axial resistance of blinding struts. The tests show that blinding can creep to failure if the sustained load exceeds a critical value that depends on the imperfection amplitude and profile as well as the strut thickness. The test results are used to validate a numerical model which is then used to carry out a series of parametric studies on full-scale blinding struts.

Notation

A_c	cross-sectional area of the member
f_t	tension cut-off
f_c	uniaxial concrete compressive strength at 28 days
h_0	notional member size in the creep model ($h_0 = 2A_c/U$)
L_{exc}	excavation width
L_g	imperfection length
P_{bi}	critical buckling resistance at time t when loaded instantaneously to failure from P_{perm}
P_{bi0}	critical buckling resistance at time t_0
P_{fc}	load at which the stress in the bottom fibre first reaches f_c when load is increased from P_{perm}
P_{fc0}	load at which the stress in the bottom fibre first reaches f_c (calculated at t_0)
P_{perm}	permanent load
$P_{\sigma_t=0}$	load at which the stress in the top fibre first reaches $\sigma_t = 0$
$P_{\sigma_t=3}$	load at which the stress in the top fibre first reaches $\sigma_t = 3 \text{ MPa}$
P_u	least of P_{bi} or P_{fc}
P_{u0}	least of P_{bi0} or P_{fc0}
t_0	age of concrete in days at first loading
U	perimeter of the member in contact with the atmosphere
w_g	imperfection amplitude

Introduction

This work was motivated by Powderham's innovative use of blinding struts on projects such as the Channel Tunnel, Limehouse Link and Heathrow Cofferdam (Powderham, 2002). The

use of blinding struts allowed much of the intermediate steel strutting that would otherwise have been required to be eliminated, resulting in considerable time savings. This in turn created a safer working environment that enabled these projects to be completed ahead of programme with considerable savings in cost and materials. Through short-term tests on one-quarter scale models and accompanying non-linear finite-element analysis (NLFEA), the authors (Abela *et al.*, 2011) have previously demonstrated that blinding struts can provide considerable compressive resistance. Blinding struts are typically constructed in the following sequence.

- The retaining walls are constructed from ground level using secant piles or other forms (e.g. diaphragm or sheet pile walls).
- The soil is excavated from between the retaining walls with additional props provided as necessary.
- The base of the excavation is carefully levelled before the blinding is cast to minimise lateral imperfections due to lack of formation flatness.
- The blinding is cast sequentially in strips and levelled to its specified thickness as the excavation proceeds along the length of the wall. In practice, the thickness of blinding varies due to constructional tolerances that induce geometrical imperfections into the strut.

Blinding struts resist axial loads from a few hours after casting until the base slab is cast, which is typically within 6 months and frequently sooner. Geotechnical analysis (Abela, 2009) shows that it is reasonable to assume, at least for the purposes of structural

design, that blinding struts are fully loaded axially during the excavation of the soil immediately ahead of the strut when the concrete is no more than a few days old. Therefore, it is important to quantify the effect of early-age concrete creep on the long-term performance of blinding struts.

The authors have previously shown (Abela *et al.*, 2011) that blinding struts typically fail in upheaval buckling (see Figure 1(a)), with the failure load dependent on strut thickness, concrete strength and geometrical imperfections that arise due to initial lack of ground flatness and subsequent ground heave. The critical elastic buckling resistance of a strut failing in upheaval buckling is least for a so-called ‘empathetic imperfection’ in which the amplitudes of the geometric and loading imperfections are equal and opposite (Croll, 1998). Furthermore, the critical buckling load is least for a strut that is initially unstressed when laid over the geometrical imperfection, even when heave is considered. In this case, Croll (1998) showed that the critical elastic buckling load is given by

$$P_{b0} = 4\pi^2 EI / L_{po}^2$$

in which EI is the flexural rigidity. L_{po} is the empathetic imperfection length, which is given by

$$L_{po} = \left(\frac{384EIw_g}{q} \right)^{1/4}$$

where q is the self-weight of the strut per unit length and w_g is the amplitude of the geometric imperfection. Vollum *et al.* (2011) extended Croll’s clamped column analogy to the design of blinding struts with imperfection lengths less than L_{po} . Cracking is accounted for in the calculation of axial resistance but not in

the calculation of flexural rigidity. Failure is assumed to occur as a result of either concrete crushing or elastic buckling. Struts with imperfection lengths below L_{po} typically fail due to concrete crushing at loads less than $P_{b0} = 4\pi^2 EI / L_{po}^2$. This analytical method is presently only suitable for the analysis of blinding struts under short-term loading, hence the need for a more sophisticated numerical modelling approach.

Abela *et al.* (2011) showed that NLFEA can accurately simulate the structural response of blinding struts under short-term loading if the geometrical and material properties are known. This paper describes a series of one-quarter scale tests on blinding struts that were carried out to examine the influence of concrete creep on buckling resistance. The experimental results are used to validate the non-linear finite-element model, including time-dependent effects, and this model is subsequently used to carry out a series of parametric studies on full-scale struts.

Non-linear finite-element analysis (NLFEA)

The NLFEA was carried out using Adaptic (Izzuddin, 1991, 2009). However, any commercially available NLFEA program could be used provided that it deals with geometric non-linearity and contact analysis as well as incorporating a suitable material model. The strut is discretised with cubic elasto-plastic two-dimensional (2D) beam–column elements incorporating both geometric and material non-linearities (Izzuddin and Elnashai, 1993). These elements are connected to the soil with joint elements modelling contact behaviour (Izzuddin, 1991, 2009) as shown in Figure 1(b), where the soil is assumed to be rigid. The joint elements are rigid in compression with zero tensile resistance. The strut is initially loaded with its self-weight before being loaded to failure with an axial load P applied through a rigid link element of variable length (see Figure 1(b)) to simulate end eccentricity.

The concrete creep model in Adaptic (Izzuddin, 2009) considers concrete to be either linear- or brittle-viscoelastic (Fragiacomo *et al.*, 2004). The behaviour is assumed to be brittle after cracking and the effect of creep is neglected in cracked fibres. The use of a linear model for concrete in compression is justified by a series of parametric studies (Vollum *et al.*, 2011) that examined the influence of concrete non-linearity on the axial resistance of blinding struts. The studies show that a linear elastic concrete model with tension cut-off gives good predictions of axial resistance if the extreme fibre stress is limited to the concrete compressive strength.

The inputs to the model are the age at first loading, the 28-day concrete compressive strength, the tension cut-off, the relative humidity and the member’s notional size h_0 . The concrete properties are related to the 28-day compressive strength in accordance with the recommendations of CEB-FIP Model Code 90 (CEB, 1993), as are the variation in concrete properties with time and the relaxation function, which is expressed in terms of a series of exponential functions using Maxwell’s rheological model. The

Figure 1. Model of strut (a) sinusoidal profile and (b) in Adaptic

model does not account for non-linear creep that occurs at compressive stresses greater than around $0.4f_c$ where f_c is the uniaxial concrete compressive strength. Three material models are used in this paper – the concrete is modelled as linear viscoelastic in model 1 and as brittle viscoelastic with tension cut-offs at $f_t = 3$ MPa (model 2) and $f_t = 0$ MPa (model 3). The 28-day uniaxial concrete compressive strength is taken as $f_c = 30$ MPa in models 1–3 throughout the paper since this is the mean value measured in the laboratory tests (see Table 1). The tension cut-off of 3 MPa in model 2 is approximately equal to the 28-day tensile strength for $f_c = 30$ MPa. The relative humidity is taken as 48%, which was the mean value recorded in the laboratory for all the analyses.

Description of test set-up

A series of seven short-term and five long-term tests were carried out on one-quarter scale models of blinding struts that were designed to simulate the behaviour of blinding struts spanning 20 m at one-quarter scale. The short-term tests have been reported previously (Abela *et al.*, 2011). All the tested specimens were 5 m long and 500 mm wide with thicknesses of 48–68 mm. The specimens were cast onto a test bed fabricated from structural steelwork as illustrated in Figure 2. A sheet of plywood was fixed to the top surface of the test bed to eliminate the minor distortions introduced into its profile by welding. A sinusoidal imperfection of wavelength 5 m and amplitude 6.3 mm was adopted in all the long-term tests in which the slab thickness was notionally 50 mm. The imperfection profile was fine tuned to within ± 0.5 mm of its specified profile by sanding the plywood fixed to the top surface of the test bed. The imperfection amplitude of 6.3 mm in the tested struts corresponds to 100 mm at full scale, which is considered an upper bound of the maxi-

Figure 2. Test rig

mum imperfection likely to arise in practice. The concrete was cast onto a polythene layer to minimise the effects of friction with the test bed.

The struts were loaded uniformly in compression at each end through a roller bearing that was in turn attached to a spherical seating. The axial load was measured with a load cell placed between the ram of the actuator and the spherical seating. Axial and transverse displacements were measured throughout the tests with transducers positioned at the ends and mid-span of the blinding strut.

Preliminary analysis of test specimens

A parametric study was carried out before the long-term tests to assess the likely effect of concrete creep on the axial resistance of struts with the same geometry and material properties as the notional test specimens. The analyses were carried out with

	Strut G	Strut I	Strut K	Strut L	Strut N
w_g : mm	6.3	6.3	6.3	6.3	6.3
Thickness: mm	50	49	52	53	52
Eccentricity: mm ^a					
Loading end	+5.3	+2.2	−0.1	+5.2	+8.0
Reaction end	+5.0	+6.1	+1.6	+5.7	+4.2
Strut end displacements: mm ^b					
Loading end	0.0	+0.6	0.0	0.0	0.0
Reaction end	0.0	−0.5	0.0	0.0	0.0
Concrete strength f_c : MPa ^c					
Day 2	19.2	17.3	13.7	13.9	20.3
Day 28	31.5	29.8	—	28.6	32.2
Failure mode	Buckling	Creep	Creep	Creep	Buckling
Days under load	2	4	0.5	71	60

^a +, above centroid; −, below centroid

^b +, upwards displacement; −, downwards displacement

^c f_c calculated as $0.8f_{cu}$ where f_{cu} is the cube strength

Table 1. Properties of struts G, I, K, L and N

Adaptic using material model 1 in which the concrete is assumed to be linearly viscoelastic.

The analyses investigated the potential influence of loading duration and amplitude on the buckling response. The struts were first loaded at 2 days (t_0) with a permanent load (P_{perm}) that was held constant for a predefined period that varied between 5 days and 2 years, unless the strut crept to failure beforehand. Subsequently, the load was increased rapidly from P_{perm} to failure. The resulting failure loads P_u are plotted against P_{perm} in Figure 3. All the loads in Figure 3 are normalised by $P_{bi0} = 230$ kN where P_{bi0} depicts the buckling resistance at t_0 when the strut was first loaded. Figure 3 shows that the axial resistance under instantaneous loading P_u is unaffected by sustained loading if P_{perm}/P_{bi0} is less than 0.7. Figure 3 also shows that the struts are predicted to creep to failure under $P_u = P_{perm}$ if P_{perm} exceeds a critical value of around $0.8P_{bi0}$. The increase in P_u with time in Figure 3 is due to the corresponding increase in the concrete elastic modulus with time.

Description of long-term tests

A total of five long-term tests were carried out. The tests were mainly designed to lie within the transition region shown in Figure 3 since this is the region where the axial resistance is least certain. All the struts were first loaded 2 days after casting. The geometrical and material properties of the tested struts are shown

in Table 1. The ends of the struts were pinned in all the long-term tests, but the axial load was applied with the eccentricities shown in Table 1. The struts were analysed with Adaptic (Izzuddin, 1991, 2009) using material model 2 with a tension cut-off at $f_t = 3$ MPa, which in this case gives similar results to model 1 with no tension cut-off as cracking only occurs at or near failure.

Tests on struts G, I and K (Table 1) were designed to investigate the effect of creep when the sustained load is large relative to the critical buckling load. Consequently, the struts either crept to failure or were loaded to failure within a few days of first loading. Tests L and N investigated the effect of applying a constant load for an extended period of around 2 months, which is thought to be representative of typical construction practice. The as-built geometrical and material properties of all the struts are summarised in Table 1 along with the loading durations. The measured and predicted failure loads are shown in Table 2. The load histories and axial and mid-span transverse displacements are plotted in Figures 4–8, which also show the response predicted with NLFEA. Further details of the loading history of each strut are summarised below.

Strut G (Figure 4) was initially loaded to 170 kN, which is 74% of the predicted axial resistance of 229 kN at first loading. The load was held at 170 kN for 2 days, after which it was increased to failure, which occurred at 251 kN due to buckling.

Figure 3. Predicted influence of creep on the buckling resistance of the tested struts ($P_{bi0} = 230$ kN)

Strut	Age of concrete at failure: days after casting	$P_{u \text{ Test}}$: kN Test result	P_u : kN FE prediction	P_{bi0} : kN FE prediction	P_{perm} : kN	P_{perm}/P_{bi0}	$P_{u \text{ Test}}/P_{bi0}$
G	4	251	235	229	170	0.74	1.10
I	6	240	240	240	240	1.00	1.00
K	2	185	185	210	180	0.86	0.88
L	73	145	—	205	145	0.71	0.71
N	62	261	250	228	150	0.66	1.14

Table 2. Measured and predicted axial resistances of tested struts

Figure 4. Influence of load on (a) axial shortening and (b) transverse displacement for strut G

Strut I (Figure 5) was initially loaded to 240 kN, which is the predicted axial resistance at first loading. The load was subsequently held at 240 kN until the following evening when the actuator was locked in place overnight to prevent failure. Conse-

quently, the load relaxed overnight, as shown in Figure 5(a). The load was increased back up to 240 kN the following morning, after which it was held constant until the evening when the actuator was again locked off. This load cycle was repeated each day until the strut failed on the fourth day under load at 240 kN. The strut was predicted to fail on the fourth day under load immediately after the load was restored to 240 kN following its drop-off over night.

Strut K (Figure 6) was initially loaded to 180 kN, which is 86% of the predicted axial resistance of 210 kN. Shortly afterwards, the transverse displacement was observed to be increasing more rapidly than expected. Consequently, the load was decreased to 150 kN at which point the transverse displacement stabilised. The load was increased to 185 kN later that day, whereupon the strut crept to failure a few hours later. The strut was predicted to creep to failure at almost the same time as that observed under $P_u = 185$ kN.

Strut L (Figure 7) was initially loaded to 150 kN (71% of the predicted axial resistance of 205 kN). The load was increased to 190 kN the following day, after which it was held constant for 2 days and then reduced to 175 kN. The load was held at this level for 23 days when it was reduced to 145 kN as the strut seemed close to failure. Subsequently, the strut crept to failure at 145 kN after 71 days under load.

Strut N (Figure 8) was initially loaded to 150 kN, which is 66% of the predicted axial resistance of 228 kN at first loading. This load was sustained for 60 days after which the strut was loaded rapidly to failure, which occurred at 261 kN.

Comparison between measured and predicted response

Inspection of Table 2 and Figures 4–8 shows that the NLFEA simulates the measured response reasonably well, with failure loads and axial displacements being predicted most accurately. The transverse displacements were generally underestimated, particularly when the strut was close to failure. This is significant since it suggests that it would be difficult to determine the axial load in a blinding strut from changes in its transverse displacement. It should be noted that the tested

Figure 5. Strut I: (a) load against time; (b) load against axial shortening; (c) transverse displacement against time

Figure 6. Load plotted against (a) time, (b) axial shortening and (c) transverse displacement for strut K

Figure 7. Load plotted against (a) time, (b) axial shortening and (c) transverse displacement for strut L

Figure 8. Influence of load on (a) axial shortening and (b) transverse displacement for strut N

struts were predicted to fail due to buckling rather than concrete crushing. The failure loads of the tested struts are plotted in Figure 3 to enable a comparison of the measured and predicted effects of sustained loading on buckling resistance. Table 2 gives the values of P_{perm} , P_{bio} and P_u adopted for the test points in Figure 3. It is noteworthy that all the test results in Figure 3 (except strut L) fit within the envelope of predicted strengths. The NLFEA is unable to capture the response in strut L as it overestimates the recovery in the transverse displacement when the load was reduced from 175 kN to 145 kN after 26 days under load. The good agreement between the measured and predicted long-term response of the blinding struts shows that the numerical model predicts the failure load sufficiently accurately under sustained load for it to be used in design.

Parametric studies on full-size struts

Four case studies are now presented to illustrate the effect of concrete creep and cracking on the buckling resistance of full-scale blinding struts with realistic imperfection profiles. The parametric studies examine the effect of sustained loading on the buckling resistance (P_{bi}) as well as the effects of concrete cracking ($P_{\sigma_t=ft}$) and crushing (P_{fc}). The struts are assumed to be 20 m long and 200 mm thick with a characteristic uniaxial concrete compressive strength of 30 MPa at 28 days. All the struts are first loaded at 3 days (t_0) with a permanent load (P_{perm}) varying between zero and the axial resistance P_{u0} . The load P_{perm} is sustained for a predefined period, varied between 28 days and 2 years, unless failure occurs beforehand, after which the strut is rapidly loaded to failure at P_u .

The imperfection profile is sinusoidal in case studies 1 to 3 and representative of that calculated in the geotechnical analysis (Abela, 2009) in case study 4. The sinusoidal imperfections are positioned symmetrically about the centreline of the excavation, as shown in Figure 1(a), with wavelength L_g . The profile from the geotechnical analysis is defined non-dimensionally in Table 3 where it is depicted as the ICFEP profile. The imperfection amplitude w_g is taken as either 50 mm or 100 mm, which is considered a practical upper bound.

The relative humidity is assumed to be 48% in the creep model in which the drying perimeter is taken as the complete section perimeter to enable a direct comparison between the results of the parametric studies and the laboratory tests. In reality, the effect of creep would be less than assumed as the relative humidity is typically around 90% outdoors. Furthermore, only

the top surface of blinding is exposed to the atmosphere in the field, unlike the laboratory tests where all surfaces were exposed.

The effect of cracking is considered by carrying out comparative analyses with the concrete modelled as linearly viscoelastic (model 1) and brittle viscoelastic with tension cut-off at $f_t = 3$ MPa (model 2) and $f_t = 0$ MPa (model 3). Table 4 gives the critical buckling resistance at first loading as well as the loads at which the peak extreme fibre stress equals f_t for models 2 and 3 ($P_{\sigma_t=ft}$) and the 28-day concrete compressive strength (P_{fc0}). The loads $P_{\sigma_t=ft}$ and P_{fc0} are calculated with the concrete elastic modulus at first loading to isolate the effects of concrete hardening and creep on P_u . The results of the parametric studies are shown in Figures 9–12.

Case study 1: $L_g = 20$ m, $w_g = 100$ mm

Case study 1 considers a full-scale strut with a sinusoidal imperfection equivalent to that in the tested struts. The buckling resistances (P_{bi0}) are almost identical for models 1 and 2 (see Table 4) since cracking first occurs near or at failure. Concrete crushing is not critical for this example. Figure 9 shows the effect of creep on the critical buckling resistance for loading durations varying between 28 days and 2 years. Creep is seen to have no discernible affect on the buckling resistance for $P_{perm}/P_{bi0} < 0.7$ where the strut fails at $P_{bi}/P_{bi0} > 1$ due to the increase in concrete stiffness while the strut is under load. The strut creeps to failure within 2 years when $P_{perm}/P_{bi0} \geq 0.7$ with the time to failure reducing as P_{perm}/P_{bi0} increases. Struts are predicted to creep to failure within 28 days when $P_{perm}/P_{bi0} > 0.9$.

x/L	0.00	0.025	0.050	0.075	0.100	0.150	0.200
$w(x/L)/w_g$	0.00	0.384	0.676	0.800	0.842	0.882	0.922
x/L	0.25	0.300	0.350	0.400	0.450	0.500	—
$w(x/L)/w_g$	0.95	0.967	0.984	0.992	0.996	1.00	—

Table 3. Normalised ICFEP profile: x/L = normalised distance along strut; $w(x/L)$ = imperfection amplitude at x/L along the strut; w_g = maximum imperfection amplitude

Case study	Profile	L_g : m	w_g : mm	P_{bi0} : kN		$P_{\sigma_t=0}$: kN	$P_{\sigma_t=3}$: kN	P_{fc0} : kN	
				Model 1	Model 2			Model 2	Model 3
1	Sinusoidal	20	100	1863	1862	1848	1862	—	—
2	Sinusoidal	5	100	2471	1651	342	909	1515	1515
3	Sinusoidal	5	50	3282	3146	2332	2826	2772	2772
4	ICFEP	20	50	2746	2475	2190	2370	2460	2460

Table 4. Axial resistances from case studies 1 to 4 at first loading

Figure 9. Case study 1. Influence of creep on buckling resistance ($P_{u0} = 1863$ kN, $L_{exc} = 20$ m, $L_g = 20$ m, $h = 200$ mm, $w_g = 100$ mm)

Case study 2: $L_g = 5$ m, $w_g = 100$ mm

This case considers the effect of reducing the imperfection length to 5 m, which is considered a practical lower bound. The effect of cracking is more critical in this case due to the greater curvature of the imperfection. This is evident in Table 4, which shows that the critical buckling resistance P_{bi0} is significantly reduced by cracking. The crushing loads (P_{fc0}) in Table 4 are the same for models 2 and 3 since the struts crack well before failure.

Figure 10(a) illustrates the effect of creep on the critical buckling resistance (P_{bi}) predicted by models 1 and 2. The results for model 3 are not included as they are identical to those obtained with model 2. The axial resistances in Figure 10(a) are normalised by the critical buckling resistance at first loading (P_{bi0}), which is 2471 kN for model 1 and 1651 kN for model 2. Figure 10(a) shows that the effect of creep is proportionately similar for cracked and uncracked struts, with struts creeping to failure within 2 years when $P_{perm}/P_{bi0} > 0.58$.

Figure 10(b) illustrates the effect of creep on the axial resistances at first cracking, crushing and buckling. The loads in the figure are normalised by P_{u0} , which equals the crushing resistance of $P_{fc0} = 1515$ kN. Figure 10(b) shows that the cracking reduces the critical buckling load P_{bi} by as much as 30% and struts creep to failure within 2 years when $P_{perm}/P_{u0} > 0.7$. The load at which tension first develops is sufficiently small for it to be unaffected by creep. Figure 10(b) also shows that creep reduces the crushing resistance of cracked struts proportionately less than the buckling resistance.

Case study 3: $L_g = 5$ m, $w_g = 50$ mm

This case considers a strut similar to case study 2 but with the imperfection amplitude reduced to 50 mm. Table 4 shows that the axial resistance is reduced by cracking as well as concrete crushing. Figure 11 shows the effect of sustained loading on the loads at first cracking, concrete crushing and buckling for

models 1 and 2. Comparison of Figures 10(b) and 11 shows that the difference between the buckling resistances given by model 1 (linear) and model 2 ($f_t = 3$ MPa) is much greater for case study 2 (~30%) than case study 3 (~5%). This is explained by the much greater loss of flexural rigidity due to cracking in case study 2 than 3.

Case study 4: ICFEP profile, $w_g = 50$ mm

Case study 4 considers the effect of P_{perm} on a strut with a profile representative of those calculated in geotechnical analyses due to heave (Abela, 2009). The imperfection amplitude of 50 mm equals the net heave that occurs due to ground consolidation over 2 years from completion of the excavation. The results of the analyses are presented in Figure 12, which illustrates the effect of sustained loading on axial resistance, and Table 4, which gives P_{bi0} , $P_{\sigma_1=f_t}$ and P_{fc0} .

Observations from the case studies

The case studies show that blinding struts can creep to failure within 2 years if P_{perm} is greater than a critical value that reduces as the curvature of the imperfection profile increases. It should be noted that the maximum possible value of P_{perm}/P_{u0} can depend on the in situ concrete compressive strength at first loading as well as its stiffness. Therefore, designers should specify the required compressive strength at first loading as well as the 28-day concrete compressive strength. The observed reductions in axial resistance due to creep are summarised in Table 5 in which the axial resistances are normalised by P_{u0} , which is taken as the least of P_{bi0} or P_{fc0} from Table 4.

The design axial resistance depends on the assumed geometrical imperfection, which should allow for construction tolerances as well as ground heave. The authors have previously suggested (Vollum *et al.*, 2011) that a safety factor of at least three should be adopted in the design of blinding struts, in which case, $P_{perm}/P_{u0} \leq 0.33$. Table 5 suggests that, in this event, creep would reduce the axial resistance under instantaneous loading by no more than 12% after 2 years. Figures 9–12 also suggest that limiting P_{perm}/P_{u0} to 0.33 would typically provide a safety factor of around 2 against the strut creeping to failure under P_{perm} within 2 years.

Conclusions

This research was prompted by Powderham's (2002) pioneering use of blinding struts in major infrastructure projects, enabling these projects to be completed several months before schedule with considerable savings in cost and materials (Powderham, 2002). The authors (Abela *et al.*, 2011) have previously demonstrated that blinding struts can resist significant short-term axial loads before failing in upheaval buckling. This paper has described a series of laboratory tests and numerical analyses that were carried out to investigate the effect of long-term loading on the axial resistance of blinding struts. The struts were loaded with a permanent load (P_{perm}) for a predefined period before being

Figure 10. Case study 2. Influence of creep on (a) buckling resistance and (b) cracking, crushing and buckling resistance after 2 years under P_{perm} . Model 1, $P_{bi0} = 2471$ kN. Model 2, $P_{bi0} = 1651$ kN, $P_{u0} = 1515$ kN. $L_{exc} = 20$ m, $L_g = 5$ m, $h = 200$ mm, $w_g = 100$ mm

loaded rapidly to failure. The numerical analysis was carried out with the finite-element program Adaptic (Izzuddin, 1991, 2009), which the authors (Abela *et al.*, 2011) have already shown to be capable of predicting the response of blinding struts under short-term loading provided the geometrical and material properties are known.

The experimental results compare well with those obtained with NLFEA using a brittle viscoelastic creep model. Parametric studies were presented to illustrate the effect of varying the magnitude and duration of P_{perm} as well as the imperfection amplitude and profile. The laboratory tests and parametric studies show the following three types of response.

Figure 11. Case study 3. Influence of creep on the cracking, crushing and buckling resistance after 2 years under P_{perm} . $P_{u0} = 2772$ kN, $L_{exc} = 20$ m, $L_g = 5$ m, $h = 200$ mm, $w_g = 50$ mm

Figure 12. Case study 4. Influence of creep on the cracking, crushing and buckling resistance after 2 years under P_{perm} . $P_{u0} = 2460$ kN. ICPEP profile, $L_{exc} = 20$ m, $h = 200$ mm, $w_g = 50$ mm

P_{perm}/P_{bio}	Reduction on P_{bio} to account for creep: %
0–0.2	0–3
0.2–0.4	3–12
0.4–0.55	12–35

Table 5. Typical reduction in failure load due to creep at 2 years

- (a) Axial resistance is unaffected by creep if the sustained load is less than a critical value that varies between $0.2P_{u0}$ and $0.7P_{u0}$ depending on the imperfection amplitude and profile.
- (b) The strut is stable under sustained load (P_{perm}) but the axial resistance (P_u) is less than it would otherwise be.
- (c) The strut creeps to failure within 2 years under a sustained load if this load exceeds a critical value of around $0.6P_{u0}$ to $0.7P_{u0}$.

The practical consequences of creep clearly depend on the imperfection profile and the factors of safety assumed in design. The parametric studies suggest that the effect of creep can usually be neglected if an overall factor of safety of at least 3 is adopted in the design of blinding struts.

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