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Yue Huang
University of New South Wales

Ehab Hamed
University of New South Wales

Stephen J. Foster
University of New South Wales

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CREEP TESTING AND ANALYSIS OF HIGH STRENGTH CONCRETE PANELS UNDER ECCENTRIC LOADING – BUCKLING EFFECTS

Yue Huang*
Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering
The University of New South Wales, Sydney, NSW 2052, Australia. yue.huang2@unsw.edu.au
(Corresponding Author)

Ehab Hamed
Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering
The University of New South Wales, Sydney, NSW 2052, Australia. e.hamed@unsw.edu.au

Stephen J. Foster
Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering
The University of New South Wales, Sydney, NSW 2052, Australia. s.foster@unsw.edu.au

ABSTRACT

This paper experimentally investigates the time-dependent behaviour of slender HSC panels with emphasize on their buckling behaviour. The results of five full-scale panels that were tested under eccentric sustained loads are presented, and the influences of aging, magnitude and eccentricity of the applied load are examined. The experimental results are compared to predictions generated by a theoretical model developed by the authors, which is based on the rheological generalized Maxwell model to account for creep and shrinkage, and on large deformations kinematics in the structural level. Cracking, tension-stiffening and aging of the concrete are taken into account.

KEYWORDS

Creep, buckling, High-strength concrete, wall, panel, test, analysis.

INTRODUCTION

Wall panels made of reinforced high-strength concrete (HSC) have found wide applications in engineering structures such as in walls, lift cores of high-rise buildings, box bridge girders, and hulls of offshore structures. HSC panels are normally slender compared to normal-strength concrete (NSC) panels due to their superior strength and stiffness, which highlight the need for investigating their buckling capacity and its deterioration with time due to creep, shrinkage and cracking of the concrete.

Vertical high-strength concrete wall panels are subjected to compression forces in general, which increase their susceptibility to buckling failures. However, in most cases, a considerable portion of the total load can be classified as sustained compression load. When this load is combined with the normal construction inaccuracies and load eccentricities, the wall undergoes increasing out-of-plane deflection with time due to creep. This may consequently lead to loss of stability, a phenomenon referred to as creep buckling (Hoff 1958; Bockhold and Petryna 2008; Hamed et al. 2010). Alternatively, the creep deformations may not necessarily lead to buckling failure but they may increase the stresses, and may decrease the residual strength of the wall when additional loads are to be applied. The dependence of the creep strains on the level of stresses that vary with time, their interaction with shrinkage and thermal strains, and the nonlinear geometrical and material response, make accurate prediction of the creep behaviour of HSC panels a challenging and difficult task.

Many efforts were devoted to study the short-term buckling behaviour of concrete panels. However, very little research appears to have been reported on their creep buckling response, especially those made from HSC (Tatsa 1989; Gupta and Rangan 1998). This paper aims to experimentally investigate the time-dependent behavior of HSC panels by conducting long-term tests on five slender panels subjected to eccentric uniaxial in-plane loads. The influences of the loading age, eccentricity, and level of the load are studied. The experimental results are compared to theoretical results based on the model in Huang and Hamed (2013). The details of the model are not presented here for brevity.

EXPERIMENTAL PROGRAM

The five tested panels were simply supported along their two short edges and loaded horizontally (see Figure 1). All panels possess the same dimensions (2700 x 460 x 100 mm for Length x Width x Thickness) and have the same longitudinal reinforcement ratio (0.22%). The reinforcements are equally placed on the top and bottom layers. The concrete cover is 20 mm. The specimens were prepared, cast and cured in the laboratory conditions and stripped off at 14 days. The details of the loading conditions are reported in Table 1. In the analyses, the actual eccentricities at the left and right ends of each panel are used, which are calculated from the concrete strains measured on the top and bottom surfaces near the two ends, as follows:

$$e_{test} = \frac{E_c I_{eff}}{N_{test}} \frac{\varepsilon_{cT-}\varepsilon_{cB}}{h} \tag{1}$$

where e_{test} is the actual eccentricity (see Table 1); N_{test}, I_{eff}, ε_{cT} and ε_{cB} are the experimental axial load, effective moment of inertia, concrete strains on the top and bottom faces of the panel, respectively. The geometric nonlinearity is neglected in Eq. (1) as the out-of-plane deflections near the ends are very small. The load level is determined as the ratio of the measured sustained load divided by the corresponding short-term failure load predicted by the theoretical model presented in Huang et al. (2014), using the measured material properties and eccentricities. The effects of loading age, eccentricity and load level are investigated by comparing the results of Panels LT3 and LT5, Panels LT2 and LT3, Panels LT1 and LT5, respectively. Panel LT4 was loaded to 75% of its short-term failure load and then the load was dropped to 62% of the failure load and held constant with time.

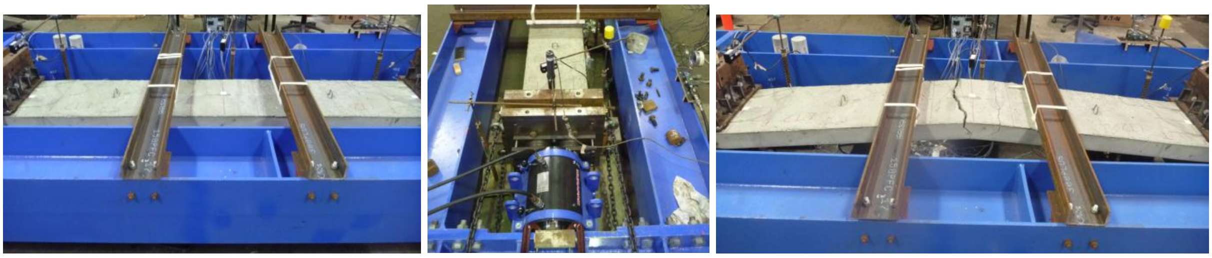
The HSC panels were tested in a universal testing frame with hydraulic jack at one end and two load cells at the other end to measure the load level. The load was applied and monitored to remain constant through the hydraulic jack. The test setup is shown in Figure 1(a) and (b) along with the buckling failure mode of the panel specimen depicted in Figure 1(c). The out-of-plane displacements were measured by three laser displacement sensors of which one was located at the mid-span and the other two were placed at 100 mm away from each end. The panel was loaded up to the desired load level first, and then the load was held constant during the creep test. Two specimens failed by creep buckling under the sustained load. The other three panels were loaded to failure at some time after initial loading by increasing the imposed load level without releasing the existing sustained load.

Concrete cylinders of 100 x 200 mm as well as concrete prisms of 100 x 100 x 500 mm were prepared along with the panels for the determination of the compressive and flexural tensile strengths of concrete. These material properties were measured at the commencement and completion of the panel test. The development of the material properties with time was determined using an interpolation method. The compressive strengths, tensile strengths and elastic moduli are 80.9 MPa, 5.9 MPa and 36.9 GPa for LT1, LT4 and LT5, and 91.7 MPa, 6.9 MPa, and 39.3 GPa for LT2 and LT3 at the age of loading. The shrinkage strain was measured using two standard concrete prisms of 75 x 75 x 280 mm immediately after the test specimens were demoulded at 14 days and the measurement stopped once the panel failed. The final shrinkage strains are 593 $\mu\varepsilon$ for LT1, LT4 and LT5, and 463 $\mu\varepsilon$ for LT2 and LT3. The creep strain was measured in a standard creep rig for each pair of panels at the same time of the test. The results are reported in Figure 2.

Table 1. Details of loading conditions

Panel No.	Loads (kN)			Eccentricity (mm)		
	Sustained load (kN)	Predicted short-term failure load (kN)	Sustained load level	[1]e_L (mm)	[2]e_R (mm)	[3]e_{design} /h
LT1	591	638	93%	22.5	21.9	1/6
LT2	320	436	73%	31.1	37.5	1/3
LT3	615	820	75%	19.1	18.8	1/6
LT4	369	593	62%	24.1	27.8	1/4
LT5	548	764	72%	19.6	21.4	1/6

[1]–Eccentricity measured at left edge; [2]–Eccentricity measured at right edge; [3] e_{design}–Designed eccentricity; h–Panel thickness



(a) Test setup: side view (b) Details of connections (c) Buckling failure

Figure 1. Long-term test set-up and representative buckling failure mode

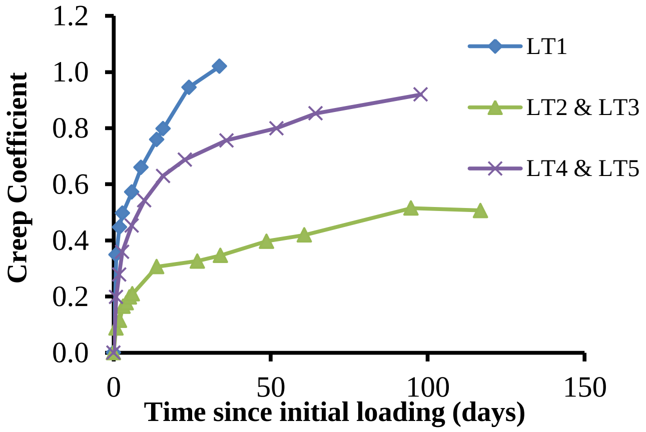


Figure 2. Creep coefficient measured in the test

EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental results as well as the predictions by the long-term theoretical model presented in Huang and Hamed (2013) are summarized in Table 2. As mentioned earlier, the predicted failure loads are based on the model in Huang et al. (2014). The measured material properties are incorporated into the long-term theoretical model. The mean value of the creep coefficients for LT1 and LT4 and LT5 are used since they were loaded in the same age. Using the least squares method to fit the experimental relaxation modulus, the spring moduli in the generalized Maxwell model (Bažant and Wu 1974) are determined. The number of Maxwell units used is taken as 5 with $\tau_\mu = 5^{\mu-1}$ (days), where τ_μ corresponds to the relaxation time of the μ-th unit. The spring constants for Panels LT1, LT4 and LT5 are 9313 MPa, 4573 MPa, 3982 MPa, 3097 MPa, 2889 MPa and 15200 MPa and the springs constants for LT2 and LT3 are 3494 MPa, 3661 MPa, 2650 MPa, 4849 MPa, 5493 MPa and 20058 MPa.

Cracking occurred to all specimens during or right after the instantaneous loading as predicted by the theoretical model. It started in the middle span and then propagated to the two edges with loading and with time. All panel specimens collapsed in buckling failure modes either with time (creep buckling) or after continuous loading to failure. The cracking regions generally concentrated within the middle one-third span of the specimens. A typical buckling failure mode is shown in Figure 1(c).

Table 2. Comparison of test results to predicted results by the theoretical model

Panel No.	Test				Prediction		
	Concrete age upon loading (t_0) (days)	Load duration (t) (days)	Failure mode	Ultimate failure load (kN)	Critical time (t)	Failure mode	Short-term failure load (kN)
LT1	22	13	Creep buckling	591	18	Creep buckling	638
LT2	146	57	Stable (crushed)	373	N/A	Stable	436
LT3	99	42	Stable (crushed)	794	N/A	Stable	820
LT4	22	104	Stable (crushed)	466	N/A	Stable	593
LT5	22	69	Creep buckling	548	107	Creep buckling	764

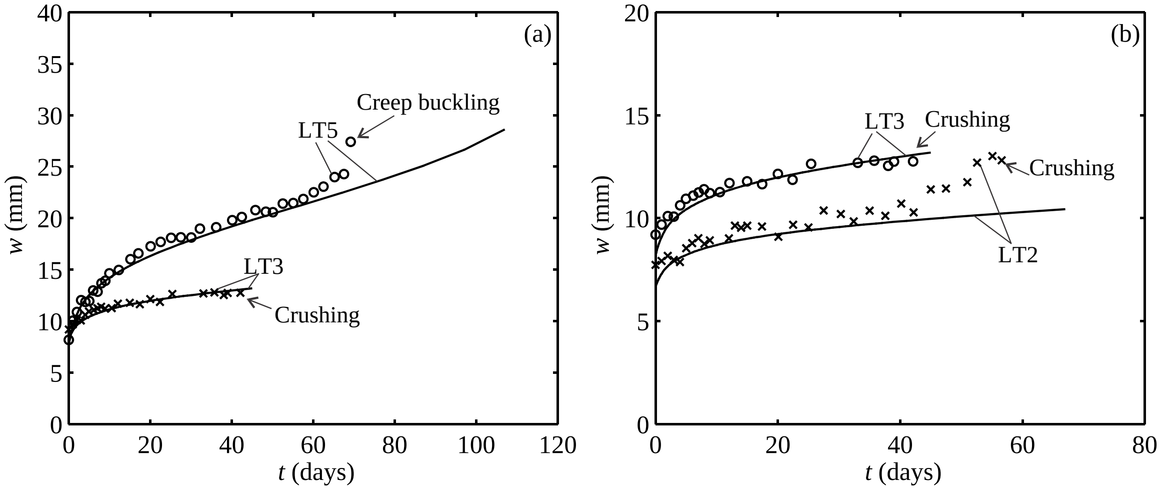


Figure 3. (a) Effect of loading age; (b) Effect of load eccentricity (ooo and +++ Test; —— Model)

The variation of the central deflections versus time is plotted in Figures 3 and 4 for all panels except LT4. It can be seen that in general the model results show close correlations with the test results, which demonstrates the capability of the theoretical model in predicting the time-dependent behavior of HSC panels. Figure 3(a) investigates the effect of loading age on the long-term behavior of the one-way HSC panel. LT3 is loaded at 99 days whereas LT5 is loaded at 22 days. The test load levels and eccentricities of these two specimens appeared not to be completely identical as it was very difficult to control the sustained load level and eccentricity in such long-term buckling test. Nevertheless, the load levels and eccentricities of both panels were close enough for comparison with each other. It can be observed that both specimens experienced increased out-of-plane deflections with time due to the combined effects of creep, shrinkage and geometric nonlinearity. In addition, the early-loaded Specimen LT5 showed a softer behavior with a larger deflection compared to Specimen LT3 that was tested at an old age. This is within the expectation since aged concrete creeps less. The predicted curves agree fairly well with the measured ones until the failure of the specimens. Specimen LT5 is characterized by a sudden buckling failure under the sustained load at 69 days after initial loading. On the contrary, Specimen LT3 was predicted to be long-term stable and the change of tested deflection with time clearly validated the prediction. Hence, the panel was crushed at t = 42 days by increasing the existing in-plane load to failure. The panel failed by buckling as well with the ultimate failure load equal to 794 kN that is fairly close to the predicted short-term load-carrying capacity.

The experimental and theoretical deflections of Specimens LT2 and LT3 are plotted against time in Figure 3(b) for the examination of the influence of the eccentricity of the in-plane load on the time-dependent response of HSC panels. Panel LT2 was tested under an eccentricity that equals to *h*/3 while Panel LT3 was loaded with a load eccentricity of *h*/6. There was a time lag in the loading age of the two specimens. However, since the two panels were cast using the same batch of concrete and they were loaded at an old age at which there is no siginifciant variation of material properties with time, the material properties of these two specimens including the creep, elastic modulus and strength are considered to be the same in the numerical model. It can be seen that as long as no creep buckling failure happens with time, changes in the eccentricity have a minor influnce on the creep response. Due to different load levels in the two panels, but with almost the same sustained load to failure load ratio, the instantaneous defleciton of Panel LT3 is larger, and the creep responses are very simlar as predicted by the model. Simliar to LT3, Specimen LT2 was going to reach a stable state eventurally as predicted by the long-term theoretical model (see Table 2). So it was loaded to failure at 57 days with an ultimate failure load of 373 kN. This failure load is about 14% smaller than the instantaneous failure load which is predicted by the short-term theoretical model, implying that creep and shrinkage effects appearred to reduce the residual strength of slender HSC panels.

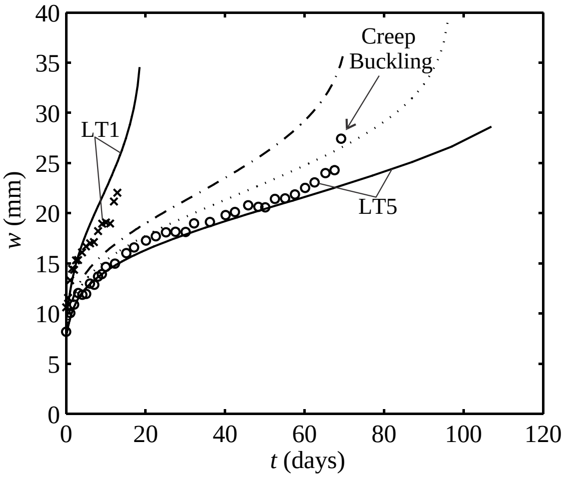


Figure 4. Effect of in-plane load level (ooo and +++ Test; —— Model; ····· Model results for LT5 with in-plane load of 75% of its failure load; — · — · Model results for LT5 with in-plane load of 77% of the its failure load); (b) Variation with time of the center out-of-plane displacement of Specimen LT4 (ooo and +++ Test; —— Model);

Figure 4 investigates the influence of the in-plane load level on the time-dependent performance of HSC panels. Specimen LT1 and LT5 were tested under 93% and 72% of the corresponding short-term failure loads, respectively, and they both failed by creep buckling at different times. It can be seen that the theoretical result of LT1 correlates with the test result reasonably well and apparently, the central deflection of Specimen LT1 which was subjected to the higher axial loads increased more rapidly than that of Specimen LT5. Consequently, Specimen LT1 failed more rapidly as well, characterized by a brittle creep buckling failure that occurred at 13 days in contrast to 69 days for Panel LT5. Good correlation also appears for LT5. It was shown previously in Huang and Hamed (2013) that the critical time to cause creep buckling is very sensitive to the load level. This theoretical observation is also validated here and explains to some extent the difference between the predicted critical time and the observed one for LT5. The load ratio used in the model was 72%, but Figure 4 shows that increasing the load level slightly by 3% or 5% can dramatically influence the time-dependent behavior and the predicted critical time, which equals to 96 days and 70 days, respectively, for load levels that correspond to 75% and 77% of the short-term load-carrying capacity of LT5. The difference between the applied loads examined in the model can be within the typical tolerances of any testing of RC structures, but the results of the long-term test investigated here are very sensitive to this parameter.

The load versus deflection for LT4 is shown in Figure 5 for the entire loading history of loading, unloading, creep under sustained load, and reloading to failure. The instantaneous load deflection curved as predicted by the theoretical model is also shown for comparison. The panel exhibited a stable behaviour under the sustained load and therefore, it was loaded to failure after 104 days since first loading. The measured ultimate strength of the panel was 466 kN, compared to 593 kN for the predicted short-term load capacity. Thus, it can be seen that under this loading scenario, creep may have a more significant impact on the residual strength of the panel, which dropped by around 21% from the short-term strength.

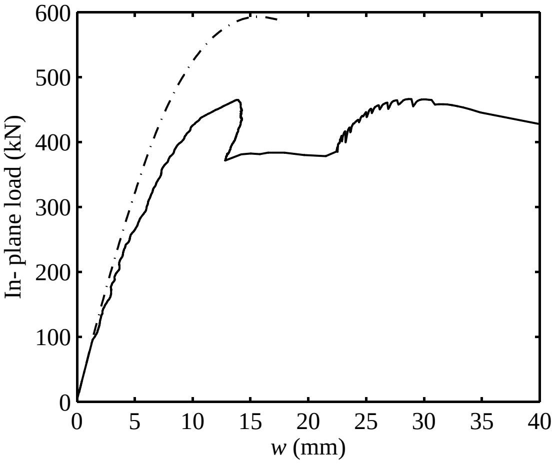


Figure 5. In-plane load vs. out-of-plane center deflection of Specimen LT4 (—— Test; — · — · Model)

CONCLUSIONS

This paper presents an experimental study of the long-term behaviour of five slender HSC panels under sustained in-plane loads. Two tested panels failed by creep buckling, and the other three panels exhibited long-term stable behaviour, and hence were loaded to failure. A good correlation is achieved between the test and theoretical results.

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