Time-Dependent Strength and Stiffness of Shear-Critical Reinforced Concrete Beams under High Sustained Stresses

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ABSTRACT:

Design and construction errors and material deterioration can lead to concrete elements being subjected to high levels of sustained stress well exceeding typical service levels. These high levels of sustained stress have led to structural collapses in the United States and around the world. However, the performance of shear-controlled concrete elements (beams and slab-column connections) under high sustained stress is not well understood. Under high sustained compressive stress (greater than 0.75fc') concrete will suffer tertiary creep characterized by accelerated permanent strain, leading eventually to a failure. The bond of the reinforcing bars to the concrete is also affected leading to slip. This research presents the results of experimental tests on shear-controlled RC beams that were loaded to 81, 86, and 92% of their short-term capacity and observed for about four weeks. Deflection and strain measurements were recorded for each specimen throughout the sustained load test. Under high sustained stress the specimens showed continued deflection with time, with most of the deflection occurring shortly after the application of load. The failure of the specimens exhibited more flexural response than that of the control specimen. The test results show that high levels of sustained stress (up to 92% of the short-term capacity) can be sustained for a prolonged time; however, the deflections and cracking are increased and the ultimate failure mode may be changed. This information will help engineers identify elements nearing failure under high levels of sustained stress.

Key words: sustained stress; shear-controlled; creep; sustained load; RC beams; slab-column connections

BACKGROUND

High levels of sustained gravity loads can exist in reinforced concrete structures due to a variety of causes including overloading, material deterioration, and design or construction errors. The high levels of sustained gravity load may lead to a time-dependent collapse of the structure. There have been numerous cases of structural collapse in the past. According to one study [1], 172 structural failures occurred in low-rise and multistory buildings in the U.S. from 1989 to 2000. Of these, 94% of the failures ended up with partial or total collapse and 45% were attributed to design or construction error, overloading, or material deficiency. Most collapses happened under sustained gravity loads. Another study [2] reported 604 failures in the U.S. from 1975 to 1989, excluding those due to natural hazards. Of those, 78% were caused by technical errors and 86% were related to RC structures. The failures resulted in 416 deaths. In contrast, according to USGS, earthquakes led to 68 deaths in the U.S. since 1990. These data highlight the likelihood of structural failure under sustained load in the U.S., where building design and construction have been rigorous. For example, the New York Wilson Hospital parking garage, a flat-plate structure, collapse in 2015 due to material deterioration. The deterioration in the reinforcement lead to the condition of high sustained stresses in the slab-column connections which eventually experienced a sudden punching failure. In other cases, structural collapse was temporarily averted such as in the Dolphin Tower condominium, a 15-story RC flat-plate building in Sarasota, Florida. Poor quality concrete lead to a condition of high sustained stresses and cracking was noticed in the 4th floor slab nearly 30 years after construction. The building was evacuated and shored to prevent failure. However, the building suffered severe damage and took nearly 5 years to repair because the functionality and safety condition could not be judged based on available knowledge [4]. Worldwide, several notable cases demonstrated the time-dependent effects of sustained high stress on RC buildings. Sampoong Department Store, a 5-story flat-plate building in Seoul, collapsed in 1995, killing 502 people [5]. Abnormal slab cracking started two months before the collapse and increased dramatically about 10 hours before the collapse.

Sustained stress results in creep in concrete under compression and macro crack growth under tension. Creep is affected by many parameters, including stress level, short-time strength, age, temperature, aggregate type and size, water-cement ratio, geometry, and humidity [6-8]. Creep is fundamentally caused by progressive propagation of internal micro cracks [9]. When the sustained stress is less than about 0.70fc', micro cracks grow slowly; however, when the stress is greater than 0.80fc', concrete experiences failure within finite time, proceeded by a rapid micro crack growth and a sharp increase in volume expansion. Of importance to structural behavior is the stress-strain response. As shown by the strength limit in (Figure 1), concrete has lower compressive strength under higher amounts of sustained loading. At low level of load the creep strain is linear with respect to the stress. Nonlinearity presents at higher stresses and, once the stress is greater than 0.75fc', the material will suffer tertiary creep characterized by accelerated permanent strain, leading eventually to a failure. Concrete, as a quasi-brittle material, is also impacted by sustained loading on macro cracking-induced fracture growth. Bažant and Xiang [11] demonstrated this property by eccentrically loading edge-notched fracture specimens subjected to tension at one side and compression at another side. Loads at 50%, 70%, and 90% of short-time capacity were applied. Crack mouth opening displacement (CMOD) initially followed power law of time and the rate of CMOD was controlled by viscoelastic creep of bulk material (Figure 2). Prior to failure, time-dependent crack growth governed the CMOD rate.

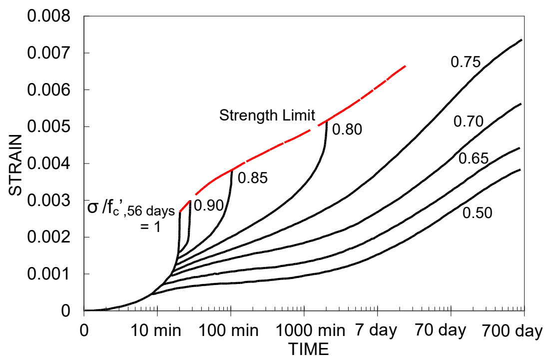


Figure 1. Concrete strength and strain under creep effect [10].

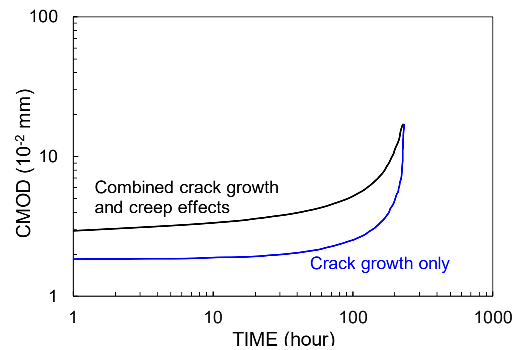
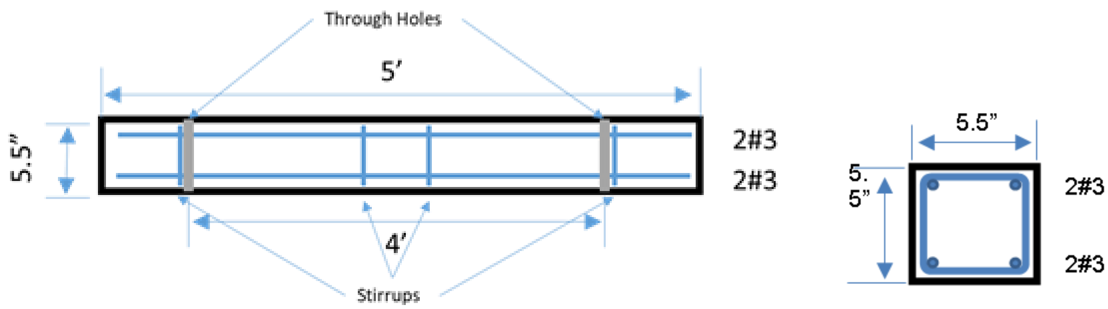


Figure 2. Time history of CMOD [11].

Very few tests have been conducted on RC beams under high sustained loads. Tests focusing on beam flexural strength [12, 13] indicate that high sustained loads have negligible impact on loading capacity. This can be expected because beam flexural strength is controlled mainly by longitudinal bars rather than concrete. However, two shear critical beams without transverse reinforcement failed in shear at 6 and 45 hours after they were applied a sustained load of 94% and 87% of their short-time shear resistance, respectively [14]. Because longitudinal bars restrain crack opening and maintain aggregate interlock, the time-dependency of crack growth in a RC beam could be less pronounced than in plain concrete. Note that all the aforementioned beams were simply supported in the tests without rotational and axial restrains at ends that actually exist in beam-column frames. This paper presents an experimental study focusing on the response of shear critical RC beams under high sustained loads.

EXPERIMENTAL SETUP

Reinforced concrete beams with a cross-section of 140 mm (5.5 in.) by 140 mm (5.5 in.) and length of 1.5 m (5 ft) were cast to investigate the effect of high sustained loads. Two No. 3 rebars (10 mm dia.) were cast both on top and bottom with a clear cover of 6 mm (0.25 in.). Each beam had two through holes cast using PVC pipes at a four-foot span length to allow threaded bars to pass through and load the beams. Four stirrups were provided in the specimen to hold the cage in the place while pouring the concrete. Their location was designed to not intersect the expected critical shear crack in the specimen. The reinforcement details and specimen dimensions are illustrated in Figure 3. Two strain gages were attached to longitudinal rebars, one on the tension (top) bar and one on the compression (bottom) bar, to record strain during the test. The test setup was created to make the beams fail under shear. Two supports were set at the third points of the four-foot test setup. The load points were at the ends of the four-foot test setup with threaded rods going through nuts, two springs, and two plates to compress them, and the PVC pipes. The threaded rods were connected to load cells, measuring the applied load. Loads were applied to the ends of the specimen by turning the nuts. The use of compression springs helped to maintain constancy of the load over time. Two linear variable differential transformers *(*LVDT's*)* were placed under the load points to measure the deflection. The test setup is exhibited in (Figure 4).



a- Longitudinal section b- Cross section

Figure 4. Specimen reinforcement and dimensions (1 in. = 25.4 mm).

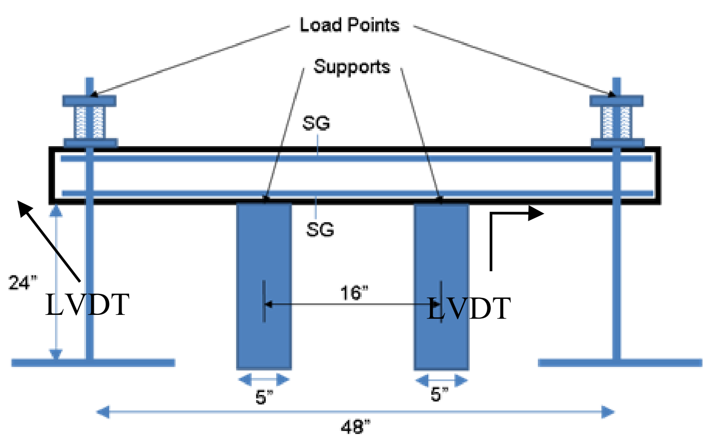


Figure 5. Test setup (1 in. = 25.4 mm).

Table 1. Material properties of all components of the tested samples

Property	Yield strength MPa (ksi)	Tensile strength MPa (ksi)	Young's Modulus GPa(ksi)
Reinforcement bars	474 (68.75)	721 (104.7)	193 (28000)

EXPERIMENTAL RESULTS

Four beam specimens were tested under high levels of sustained loads under four-point bending. As a control specimen, one beam was loaded monotonically to failure. The rest of the beam specimens were subjected to high sustained loading as a ratio of the peak load of the control beam for periods between 24 days and 42 days. Afterward, the specimens were loaded up to failure.

Control Beam Test

The control specimen was used to determine the failure mode and the critical load without applying sustained loaded. During the test of this specimen, cracks appeared at a load of approximately 6.2 kN (1400 lb) and the longitudinal reinforcement yielded at a load of approximately 15.5 kN (3500 lb). The load versus deflection response for each beam is plotted in Figure 5. The beam failed at a load of 19.9 kN (4472 lb) and a deflection of 12.4 mm (0.49 in.). Although flexural yielding of the reinforcement occurred, failure was caused by a sudden shear crack as shown in Figure 6.

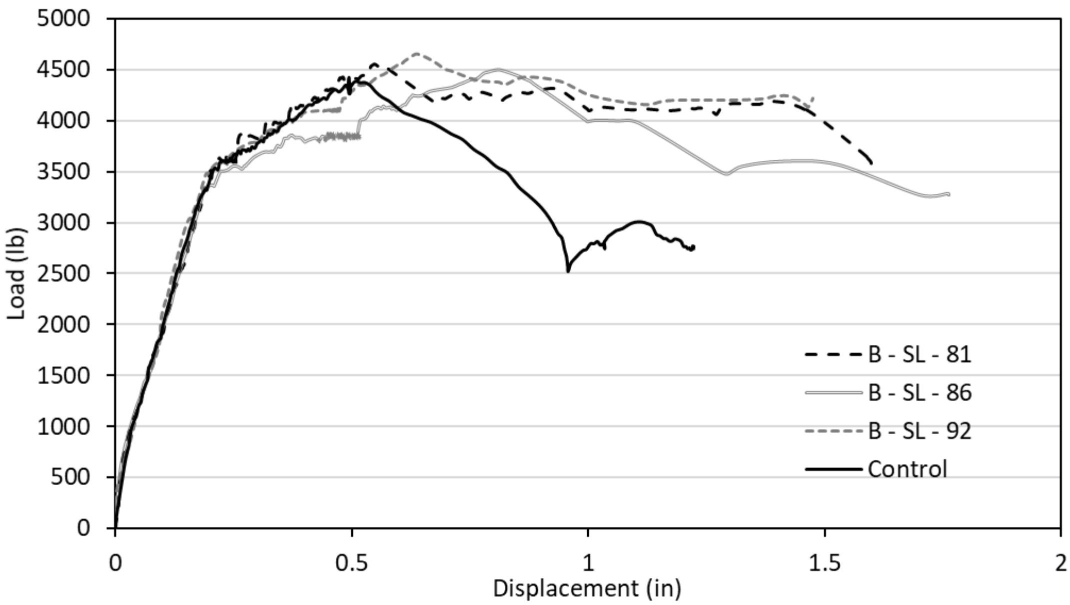


Figure 5. Load vs. deflection response.

Figure 6. Shear failure mode of the control test.

Sustained Load Beam Tests

Three additional beams were loaded at 81 percent or 16 kN (3600 lbs) (B-SL-81), 86 percent or 17.1 kN (3850 lbs) (B-SL-86) and 92 percent or 18.2 kN (4100 lbs) (B-SL-92) of the control beam peak load (19.9 kN) for a loading duration of 25, 24, and 42 days respectively. None of the beams failed under the sustained loading. Therefore, the sustained loading test was terminated and the beams were loaded monolithically to failure.

The load deflection responses of the sustained load beam tests were similar to each other and to the control beam (Figure 5), with the exception of beam B-SL-86 which exhibited an overall softer response. Figure 7 highlights the region of sustained loaded on the load deflection graph. As can be seen in Figure 7, the sustained loading resulted in additional deflection in the specimen. When loading was resumed, the load deflection curve continued to increase and met the original control loading curve.

The performance of beams during sustained load is exhibited in Figure 8. The load was maintained nearly constant for the period of sustained loading. The deflections in Figure 8 have been normalized to consider only the deflections occurring under sustained load. Deflections increased under sustained loads. Most of the deflections occurred in the early periods of loading. Table 2 summarizes the increases in the beam deflections with periods of time under sustained loads. At least 56 percent of deflections occurred in the first seven days for all specimens. Higher sustained loads meant higher percentages of deflections, at least in the first two weeks. Although the test of specimen B-SL-86 was tested for a period of 42 days, 58 percent of deflection occurred in the first seven days. However, even at 24 days, specimen B-SL-86 deflected more than the other two specimens, which can be attributed to that specimen B-SL-86 was initially less stiff than the others.

The total sustained load deflection was significantly less than the deflection at peak load for the three beams as shown in Table 3. The percentages of deflection of specimen B-SL-81, specimen B-SL-86, and specimen B-SL-92 under the sustained load of the deflection at failure were 6.6 %, 15.9%, and 8.2% respectively. Based on the percentages, it is unlikely that the beams would fail under continued sustained loading because the increase rate in deflection became smaller with time.

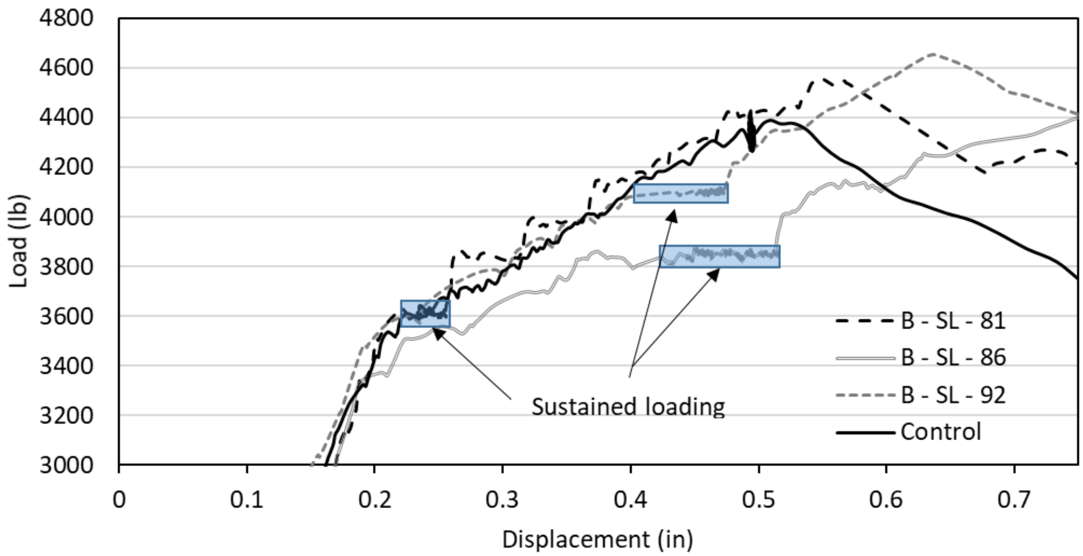


Figure 7. Regions of sustained loading on load deflection graph

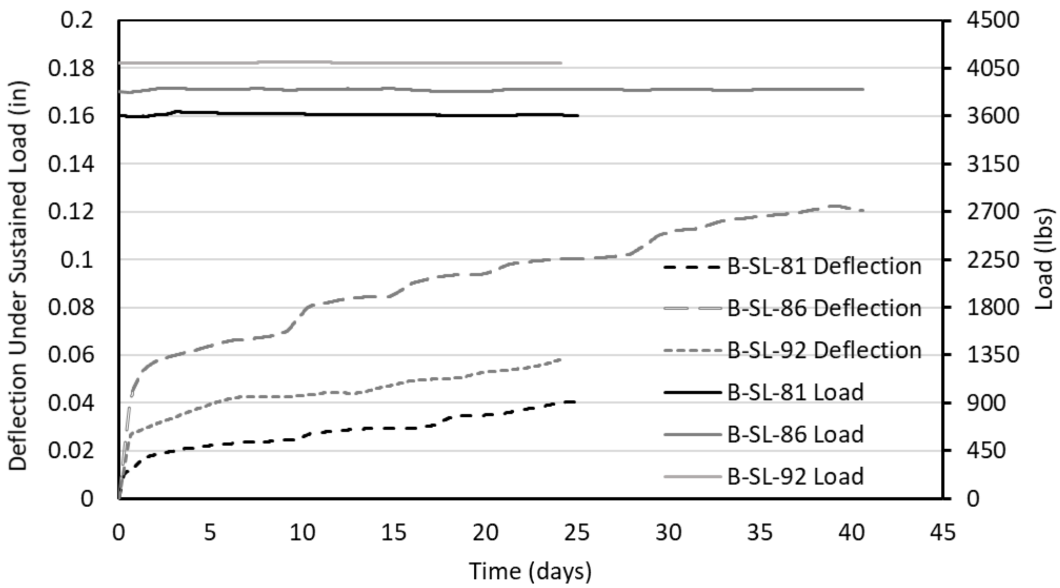


Figure 8. Sustained load and deflection vs. time.

Table 2. Summary sustained load deflection with periods of time

B-SL-81			B-SL-86			B-SL-92		
Period (days)	Increase in deflection (in)	Percentage (%)	Period (days)	Increase in deflection (in)	Percentage (%)	Period (days)	Increase in deflection (in)	Percentage (%)
0	0	0	0	0	0	0	0	0
7	0.0203	56	7	0.0735	58	7	0.0424	73
14	0.0259	71	14	0.0912	72	14	0.0461	79
21	0.0318	87	21	0.1047	82	21	0.0539	92
25	0.0364	100	41.8	0.1274	100	24	0.0583	100

Table 3: Peak loads and deflections for all beams

Beam	Peak load (lb)	Sustained load deflection (in.)	Deflection at peak load (in.)	Deflection at Failure (in.)
Control	4472	-	0.49	1.22
B-SL-81	4559	0.04	0.55	1.60
B-SL-86	4498	0.12	0.80	1.76
B-SL-92	4649	0.06	0.71	1.47

At failure all beams under sustained loads exhibited a different failure than the control beam. The control beam suddenly failed in shear at the peak load. However, the beams that experienced sustained loading exhibited significantly more deflection, cracking, and crushing of the concrete before shear failure as exhibited in Figure 8, 9, and 10. Specimen B-SL-92 exhibited nearly a total flexural failure with the shear crack being very vertical over one of the loading points. Peak loads, deflections at peak loads, and overall deflections are given in **Table 3** and the load deflection curve in Figure 5. The deflections at failure for the sustained load specimens were 31%, 44%, and 21% higher than the control beam. The difference in the failure appearance and deflection indicates that the sustained loaded did affect the beam. The affect likely took place in possible slipping of the reinforcement to concrete bond and micro-cracking within the concrete. The change in failure appearance yet lack of failure under sustained load, may be due to the fact that the tested beams were near to their flexural capacity. The sustained load increased the flexural response of the beams and delayed the shear failure.

Figure 9. Failure of B-SL-81.

Figure 10. Failure of B-SL-86.

Figure 11. Failure of B-SL-92.

CONCLUSIONS

This research presents the results of experimental tests on shear-controlled RC beams. A four beams were tested under a four-point bending test. One beam was tested under monotonic increasing load as a control beam while the other beams were tested under sustained loads. The three beams loaded under sustained load were loaded to 81, 86, and 92 percent of the control beam capacity and observed for periods of 25 days, 24 days, and 42 days. The results of the test showed the following conclusions:

- Sustained loading in these beams did not result in failure of the beam. Although high levels of sustained stresses have caused failures in past structures, sustained loading in the tested beams did not result in failure.
- Beams did experience continued deflection under sustained loading. Beams experienced at least 50 percent of their deflection under sustained load within the first four days. After the initial rapid deflection, the deflection continued to increase at nearly a linear rate.
- The total deflection under sustained load for beams was very small (about 7 percent) of their overall deflection. For the beams tested, it is unlikely they would have failed under sustained load if the test was continued for a longer period of time.
- The overall deflection of the sustained load beams was about 30% higher than that in the control test and the failure appearance of the beams that had experience sustained load exhibited much more flexural cracking and concrete crushing than the control specimen.
- The failure loads of sustained load beams were approximately the same as in the control test.

Additional testing is needed to further investigate the effect of high sustained loads in reinforced concrete members. Beam specimens of varying flexure to shear capacities, bond tests, and slab-column connection tests would further the research.

REFERENCES

(1) Wardhana, K. and Hadipriono, F. (2003). “Study of Recent Building Failures in the United States,” Journal of Performance of Constructed Facilities, 17(3), 151-158.

(2) Eldukair, Z. A. and Ayyub, B. M. (1991). “Analysis of Recent US Structural and Construction Failures.” Journal of Performance of Constructed Facilities, 5(1), 57-73.

(3) TWC News (2015). “Structural Engineer: Ramp Likely Showed Signs of Deterioration Prior to Collapse,” July 17, 2015.

(4) Hill, B., Kuykendall, R., and Moore, M. (2011). Final report to Merlin Law Group on 4th floor Distress of Dolphin Towers WJE No. 2010.3594, Wiss, Janney, Elstner Associates, Inc, Duluth, GA.

(5) Gardner, N. J., Huh, J., and Chung, L. (2002). “Lessons from Sampoong Department Store Collapse,” Cement and Concrete Composites, 24 (2), 523-529.

(6) Bažant, Z. P. (1975). “Theory of Creep and Shrinkage in Concrete Structures: A Precis of Recent Developments,” Mechanics Today, Vol. 2, pp. 1-93, Pergamon Press.

(7) Iravani, S. and MacGregor, J. G. (1998). “Sustained Load Strength and Short-Term Strain Behavior of High-Strength Concrete,” ACI Structural Journal, 95(5), 636-647.

(8) Mazzotti, C. and Savoia, M. (2002). “Nonlinear Creep, Poisson’s Ratio, and Creep-Damage Interaction of Concrete in Compression, ACI Material Journal, 99(5), 450-457.

(9) Shah, S. P. and Chandra, S. (1970). "Fracture of concrete subjected to cyclic and sustained loading," ACI Journal Proceedings, 67(10), 739-758.

(10) Rüsch, H. (1960). "Researches toward a General Flexural Theory for Structural Concrete," ACI Journal Proceedings, 57(7), 1-28.

(11) Bažant, Z. P. and Xiang, Y. (1997). "Crack Growth and Lifetime of Concrete under Long Time Loading," Journal of Structural Engineering, 123(4), 350-358.

(12) Washa, G. W. and Fluck, P. G. (1953). "Effect of sustained overload on the strength and plastic flow of reinforced concrete beams," ACI Journal Proceedings. 50(9), 65-72.

(13) Reybrouck, N., Criel, P., Caspeele, R., and Taerwe, L. (2015). "Modelling of Long-Term Loading Tests on Reinforced Concrete Beams," Proceedings of the 10th International Conference on Mechanics and Physics of Creep, Shrinkage, and Durability of Concrete and Concrete Structures, Vienna, Austria, September 21-23, 745-753.

(14) Sarkhosh, R., Walreven, J., Uijl, J. D., and Braam, R. (2013). "Shear Capacity of Concrete Beams under Sustained Loading," IABSE Symposium Report, 99(31), 162-169.