Time Dependent Strength and Stiffness of Shear Controlled 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 percent 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 their 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 (Wardhana et al. 2003), 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 (Eldukair et al. 1991) 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, collapsed in 2015 due to material deterioration. The deterioration in the reinforcement led 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 (Hill et al. 2011).

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 (Gardner et al.2002). 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-term strength, age, temperature, aggregate type and size, water-cement ratio, geometry, and humidity (Bažant 1975, Iravani et al. 1998, and Mazzotti et al. 2002). Creep is fundamentally caused by progressive propagation of internal micro cracks (Shah et al. 1970). 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 the lowest compressive strength under sustained loading with lower compressive strength under higher amounts of sustained loading. At low levels 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 et al. (1997) 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 with respect to 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.

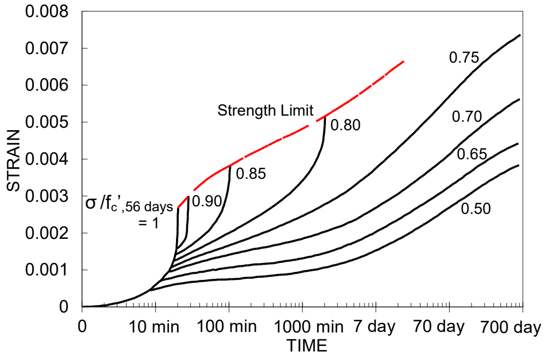


Figure 1. Concrete strength and strain under creep effect (Rüsch 1960).

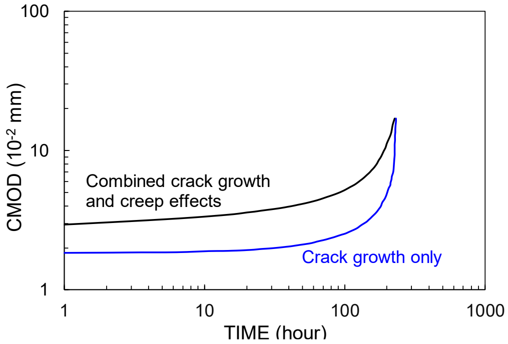


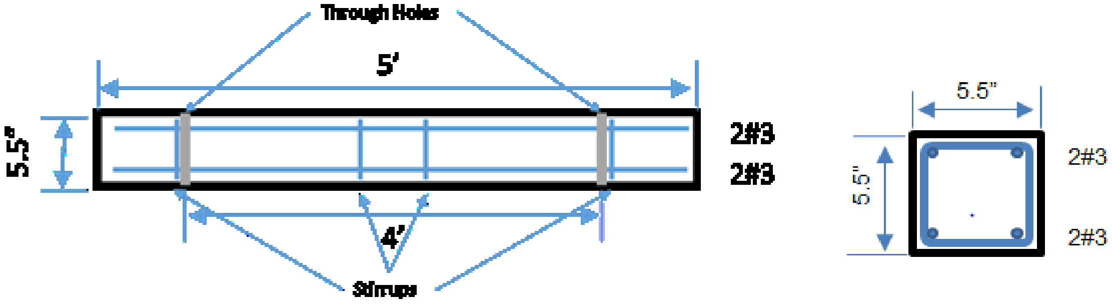
Figure 2. Time history of CMOD (Bažant et al. 1997).

Very few tests have been conducted on RC beams under high sustained loads. Tests focusing on beam flexural strength (Washa et al. 1953, Reybrouck et al. 2015) 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. Furthermore, 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. 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 (Sarkhosh et al. 2013). This may indicate that shear-controlled reinforced concrete members may be more vulnerable to high levels of sustained loading. 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 a preliminary 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 designed induce a shear critical failure mode. Two supports were set at the third points of the test span. The load points were at the ends of the four-foot test span with threaded rods going through nuts, load cells, springs, and plates and attached to the lab's reaction floor. 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. Load levels were checked twice a day for the first 5 days and every day thereafter. 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). Steel reinforcement material properties are summarized in (Table 1). The concrete compressive strength was 36 MPa (5250 psi).



a- Longitudinal section

b- Cross section

Figure 3. Specimen reinforcement and dimensions (1in. = 25.4 mm).

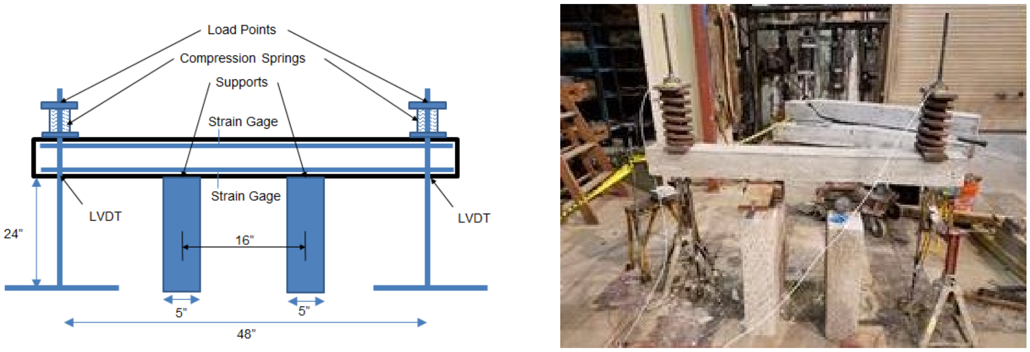


Figure 4. Test setup (1in. = 25.4 mm, photo by S. Orton).

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 subjected to monotonically increasing load until failure. The remaining beam specimens were subjected to high sustained loading for periods between 24 days and 42 days. The level of sustained load was 81, 86, and 92 percent of the control beam capacity. After the sustained load, the load on the beams was increased until failure.

Control Beam Test

The control specimen was used to determine the failure mode and the critical load of a beam without applying a high level of sustained load. In the control beam test, cracks appeared in the specimen at a load of approximately 6.2 kN (1400 lb) under each loading point and steel yield occurred at a load of approximately 15.5 kN (3500 lb). The load versus deflection is plotted in Figure 5. The load is the average load under the two loading points and the deflection is the average deflection measured at the two ends of the beams. Due to the simple setup, the load and deflection on each end were similar throughout testing. The only exception is near the end of the response when failure (damage) on one side of the beam lead to greater deflections on that side. The control 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.

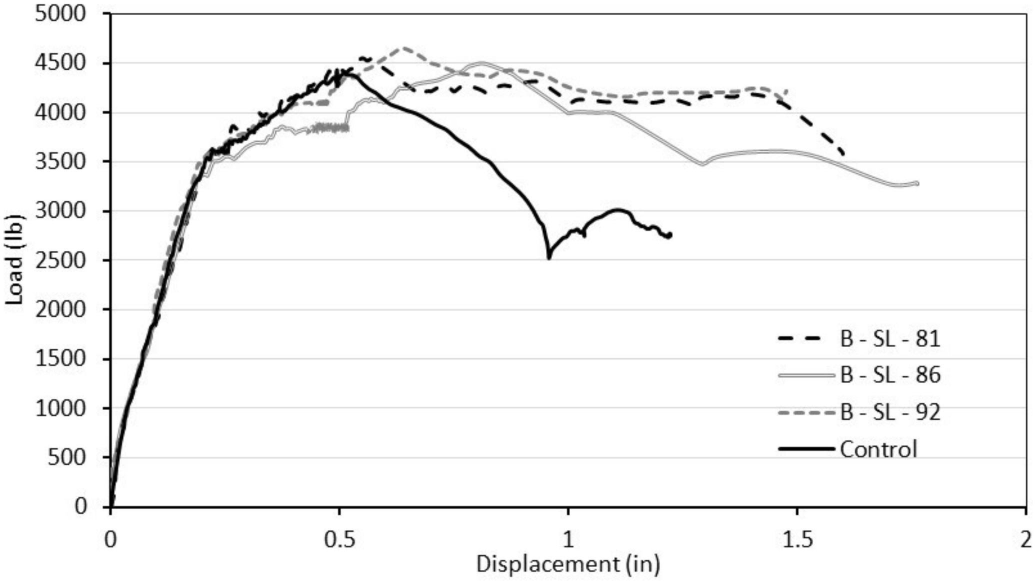


Figure 5. Load vs. deflection response (1in. = 25.4 mm, 1 lb = 4.44N)

Figure 6. Shear failure mode of the control test (photo by S. Orton).

Sustained Load Beam Tests

Three additional beams were loaded at a sustained load level of 81 percent (16 kN (3600 lbs)) B-SL-81, 86 percent (17.1 kN (3850 lbs)) B-SL-86 and 92 percent (18.2 kN (4100 lbs)) B-SL-92 of the control beam peak load, 19.9 kN (4473 lbs), for periods of 25, 42, and 24 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 response during sustained load 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. Table 2 summarizes the increases in the beam deflections with periods of time under sustained loads. Most of the deflection occurred in the early periods of loading. 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 may be due to a reduced stiffness in specimen B-SL-86.

The strain measurements showed a similar response as the deflection. The absolute strain in the top and bottom reinforcement increased the most during the first few days of loading. However, the strain continued to increase throughout the testing. The increase in strain indicates that the reinforcement was taking more load, probably due to creep within the concrete, as the sustained loading continued. There may have also been slip of the reinforcement to concrete bond.

The amount of deflection that occurred during sustained loading 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, B-SL-86, and B-SL-92 during sustained loading were 7.2%, 15%, and 8.4% respectively of the deflection at peak load. The low levels of deflection under sustained load, and declining rate of deflection with time make it unlikely that the beams would have failed under sustained load.

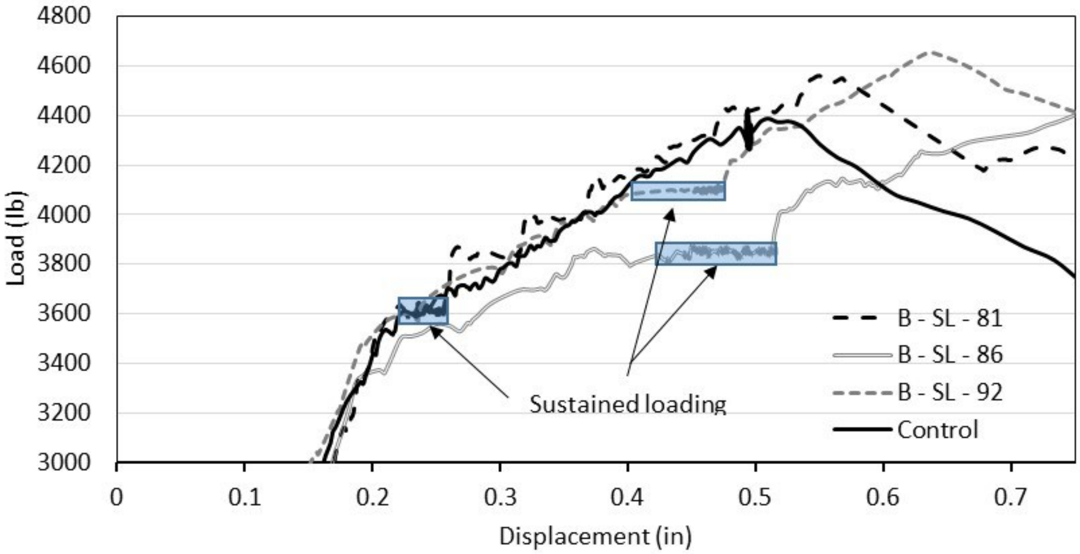


Figure 7. Response during sustained loading (1in. = 25.4 mm, 1 lb = 4.44N).

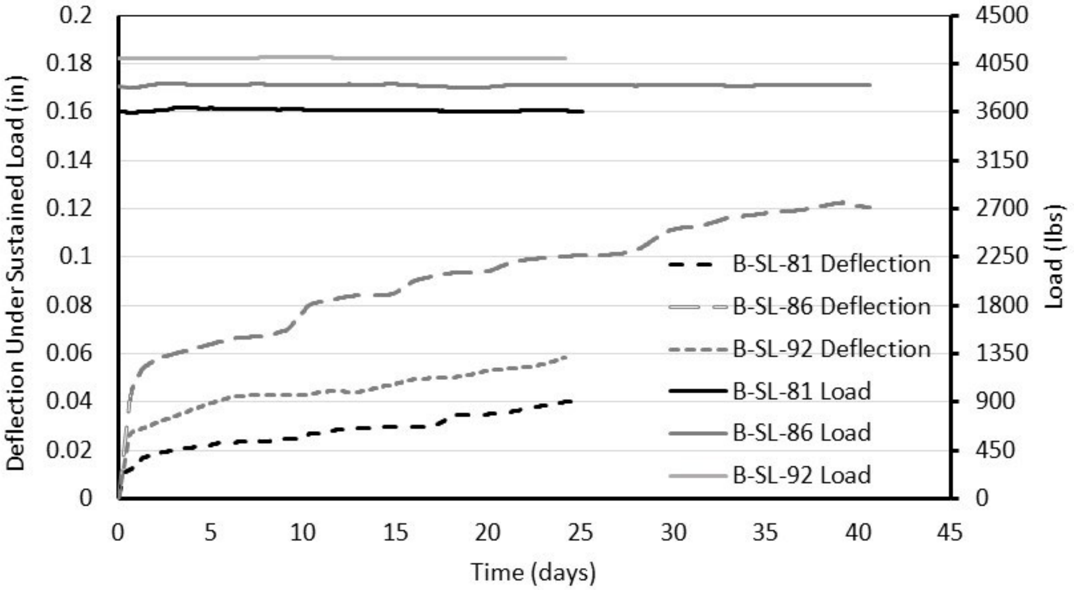


Figure 8. Sustained load and deflection vs. time (1 in. = 25.4mm).

Table 2. Summary sustained load deflection with periods of time

B-SL-81			B-SL-86			B-SL-92		
Period (days)	Deflection increase mm. (in.)	Percentage (%)	Period (days)	Deflection increase mm. (in.)	Percentage (%)	Period (days)	Deflection increase mm. (in.)	Percentage (%)
7	0.52 (0.02)	56	7	1.88 (0.074)	58	7	1.07 (0.042)	73
14	0.66 (0.026)	71	14	2.31 (0.091)	72	14	1.17 (0.046)	79
21	0.81 (0.032)	87	21	2.67 (0.105)	82	21	1.37 (0.054)	92
25	0.92 (0.036)	100	41.8	3.23 (0.127)	100	24	1.47 (0.058)	100

Table 3: Peak loads and deflections for all beams

Beam	Peak load kN (lbs)	Sustained load deflection mm. (in.)	Deflection at peak load mm. (in.)	Deflection at Failure mm. (in.)
Control	19.9 (4472)	-	12.45 (0.49)	31 (1.22)
B-SL-81	20.28 (4559)	1.02 (0.04)	13.97 (0.55)	40.64 (1.60)
B-SL-86	20 (4498)	3.05 (0.12)	20.32 (0.80)	44.7 (1.76)
B-SL-92	20.68 (4649)	1.52 (0.06)	18.03 (0.71)	37.34 (1.47)

All beams under sustained load exhibited a different failure behavior 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 6. 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 effect 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 seemed to increase the flexural response of the beams and delayed the shear failure.

Figure 9. Failure of B-SL-81 (photo by S. Orton).

Figure 10. Failure of B-SL-86 (photo by S. Orton).

Figure 11. Failure of B-SL-92 (photo by S. Orton).

CONCLUSIONS

This research presents the results of experimental tests on shear-controlled RC beams. 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, 42 days, and 24 days. The results of the tests showed the following conclusions:

- Although high levels of sustained stresses have caused failures in past structures, sustained loading in the tested beams did not result in failure (reduction in load carrying capacity).

- The failure appearnce of the beams that were loaded with sustained load exhibited a greater amount of flexural cracking and concrete crushing than the control beam. However, the peak loads of sustained load beams were approximately the same as in the control test.
- Sustained loading did result in increasing deflection in the beam. 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 amount of deflection that occurred under sustained load was very small (about 7 percent) of the overall deflection at peak load. 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.

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, reinforcement to concrete bond tests, and slab-column connection tests would further knowledge in this area.

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