Shear-critical reinforced concrete beams under sustained loading Part I: Experiments

Reza Sarkhosh, Joost Walraven, Joop den Uijl

Delft University of Technology, Faculty of Civil Engineering and Geosciences, Group of Concrete Structures, the Netherlands

Several experiments were carried out on reinforced concrete beams without shear reinforcement subjected to high sustained shear loads close to the short-term failure load. The goal was to investigate the behaviour of shear-critical concrete beams under sustained loading. The beams were subjected to the load for a minimum period of three months. Meanwhile, the deflection, crack growth and crack widths were measured. A total number of 42 reinforced concrete beams have been tested. Amongst them, 24 beams were tested under monotonically increased short-term loading, in order to obtain reference values for the shear resistance, the crack width and the type of failure, and to gain insight into the scatter of the results. The 18 other beams were subjected to long-term sustained loading with high load levels: the ratio of applied shear load to short-term shear resistance was between 0.87 and 0.975. Furthermore, at the end of the period of long-term loading, the concrete beams were tested to failure. The program was carried out in order to determine advanced rules for the shear bearing capacity of existing bridges in The Netherlands. For the full background information reference is made to Sarkhosh (2014)

1 Introduction

Shear failure of reinforced concrete beams without shear reinforcement is characterized by an instantaneous brittle failure mode and is complicated by the behavior of the inclined shear crack, and in relation to that the contribution of the effects of aggregate interlock and dowel action. The time-dependency of the shear-critical beams is even more complicated by the role of time effects such as creep and shrinkage, development of concrete strength, crack opening displacements, creep of bond and stress redistribution in the RC member. It is well-known that the shear resistance of structural members without shear reinforcement depends on the concrete strength. Therefore it was an important observation that the concrete strength, as measured on drilled concrete cores taken from existing bridges, is substantially higher than the original concrete design strength. The most important explanation for this is that in the old days cement with coarse particles was used. For that reason, the cement hydration continued for many years after determining the 28-days strength. In many cases, concrete compressive strength values between 60 and 100 N/mm^2 (8700-14500 psi) were found, whereas the original 28-days characteristic compressive strength was often only 25 N/mm^2 (3625 psi). This was a very welcome observation, because it would mean the shear bearing capacity of those old bridges is substantially higher than the original design capacity, which could mean that many bridges do not have to be strengthened, although they are subjected to larger traffic loads than foreseen in the original design. A point of uncertainty is, however, the behavior of concrete under sustained loading. In design recommendations sustained loading factors are used for the concrete design compressive and tensile strength. Since the shear bearing capacity depends on the concrete strength it seems logic that sustained loading factors should be applied for the shear bearing capacity as well.

In most codes, reduction factors on the compressive and tensile strength of the concrete under sustained loading are prescribed, and it seems therefore logical that they should apply for shear as well. In the Eurocode 2 for concrete structures, EN 1992-1-1, the sustained loading factor is a nationally defined parameter, which can be chosen by the individual countries between 0.8 and 1.0. In the *fib* Model Code (2010) the sustained loading factor for normal strength concrete subjected to tension is as low as 0.6. Many countries, like the Netherlands, have chosen nevertheless for the sustained loading factor a value of 1.0 both for concrete in tension and compression, arguing that the concrete design strength is determined based on concrete with an age of 28 days, and an eventual sustained loading effect is compensated by further strength development. Whether or not a sustained loading factor should be applied when assessing the shear resistance of existing concrete solid slab bridges, is a question with large consequences.

2 Development of an experimental program on the effect of sustained loading on the shear capacity

*2.1 **Details of the reinforced concrete beams used in the test program***

The reinforced concrete beams were designed for shear failure. Therefore, sufficient longitudinal reinforcement was provided to guarantee a sufficiently large bearing capacity in bending. The shear critical beams were designed based on an FE analysis with ATENA

2D (2012). The beams were cast in seven series of casting batches, where all series consisted of six identical beam specimens, in combination with 36 cubes for compression testing. The loading configurations and the dimensions of the beams are shown in Figure 1 and the details of the cross section and concrete strength are given in Table 1. The shaded columns in this table represent the variables in the different series.

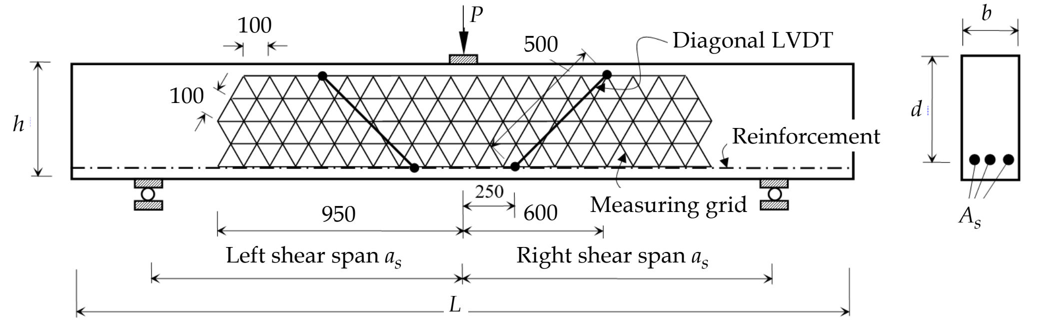


Figure 1. Reinforced concrete beam specimen subjected to three-point bending

Table 1. Details of the reinforced concrete beams

Series	$f_{c,cube,28days}$	h	b	d	L	a_s	$\frac{a_s}{d}$	A_s	ρ
No.	MPa	mm	mm	mm	mm	mm		mm²	%
1	38.2	450	200	410	3000	1200	2.93	942	1.15
2	34.6	450	200	410	3000	1200	2.93	942	1.15
3	48.4	450	200	410	3000	1200	2.93	942	1.15
4	45.2	450	200	410	3000	1200	2.93	942	1.15
5	44.1	450	200	410	3000	1200	2.93	942	1.15
6	81.2	450	200	407	3000	1200	2.95	1472	1.81
7	80.7	450	200	407	3000	1200	2.95	1472	1.81

2.2 *Test set-up*

Six parallel long-span testing frames with capacities up to 400 kN have been built in a climate conditioned room to perform the three-point bending tests in parallel. Each equipment, consisted of a rigid steel frame and the following elements:

- A hydraulic actuator with a capacity of 400 kN that applies the load.

- A hydraulic bladder accumulator to keep the oil pressure inside the hydraulic system constant during the long-term loading.
- A load cell with a capacity of 400 kN and an accuracy of 0.33% installed between the actuator and the loading plate.
- A loading plate placed at the middle of the beam with a dimension of 50×100×200 mm (height, length, width) that covers the width of the beam.
- A linear variable displacement transducer (LVDT) with 20 mm measuring range at the middle next to the loading plate.
- Two roller supports, each one with a contact area of 100×200 mm.
- A pair of LVDT's with 10 mm measuring range, diagonally installed in both shear spans.
- Additional measuring equipment with a manually operated LVDT (Measuring range = 20 mm) applied on specimens in Series 5-7.

The zero reference measurements were conducted in the stage that the beams were only loaded by their dead-weight. Thus, the influence of the concrete dead-weight is not incorporated in the measuring results. All tests have been carried out in a load-controlled mode, whereas the application of the load was performed manually through a hand-operated hydraulic pump.

For the purpose of measuring the diagonal deformation of the beam, a pair of diagonal LVDTs was used. These LVDTs have a measuring length of 500 mm and were installed diagonally whereas the bottom hinge is at a distance of 200 mm and the top hinge at a distance of 650 mm from the midspan, see Figure 1. The location of the diagonal LVDTs covers the area of the expected diagonal shear tension crack.

With the aim of measuring the surface strains and monitoring the crack opening in detail, a measuring grid consisting of 241 lines and 96 points has been attached at the front side of the beam (Fig. 1). The grid consists of 96 nodes at 100 mm distance from each other, placed along 5 rows. Steel reference points with an outer diameter of 8 mm have been mounted at each node. Later on, by means of a demountable displacement transducer, the relative displacement of the reference points was measured.

3 Results of short-term monotonic loading tests

3.1 Overview of the short term test program

The ultimate load P_u is considered to be the highest peak load in the load-deflection curve. When calculating the shear resistance V_u , the self-weight of the beam was also included ($V_u = \frac{1}{2} P_u + \frac{1}{4} m_b g$). For the concrete beams listed in Table 2, the ultimate load and the shear resistance of the beams are given together with a statistical analysis of each series. The statistical evaluation on each series displays a small scatter and the mean value of shear strength has a low coefficient of variation of less than 6.08%. It can also be seen from Table 2 that for each series the lower confidence limit, that is the 5% fractile value of V_u , is only slightly lower than the mean value.

3.2 Summary of the short-term tests

A brief summary of the results of the short-term test on concrete beams without shear reinforcement is given in the sequel:

- 28 short-term monotonic three-point bending tests have been conducted on shear-critical reinforced concrete beams. The test results per series show a relatively small scatter of V_u with a coefficient of variation smaller than 6.08%.
- The mean value of the shear resistance $V_{u,\text{mean}}$ in any series will be used as the reference value for the shear resistance of the same series when testing beams under long-term loading.

4 Results of sustained loading tests

As discussed earlier, the concrete beams have been subjected to sustained loading for periods between 2.5 hours (shortest time until shear failure) and 1344 days (end of the program). The goal was to study the behaviour of shear cracks under high levels of sustained loading, with loads close to the shear resistance. The sustained loading tests were started directly after completing the monotonic term tests. During the sustained loading tests, the crack width development, the crack length development and the appearance of new cracks have been monitored.

The load intensity factor $\lambda = V_{\text{sus}}/V_{u,\text{mean}}$ for the various beams was chosen to be between 0.86 and 0.98, as given in Table 3. When the beam was loaded over 0.9 $V_{u,\text{mean}}$, it was practically beyond the lower confidence limit of the short-term shear resistance. Therefore,

Table 2. Shear resistance under short-term monotonic tests

Series	Label	Age at t_0	Loading time *	P_u	V_u	$V_{u,\text{mean}}$	COV	$LCL_{5\%}$†
		days	sec	kN	kN	kN	%	kN
1	S1B1	28	224	192.03	97.31	93.66	4.53	86.68
	S1B2	28	92	176.14	89.37			
	S1B3	28	194	195.04	98.82			
	S1B4	28	258	174.15	88.37			
	S1B5	32	176	188.03	95.31			
	S1B6	32	162	182.95	92.77			
2	S2B1	70	201	181.82	92.21	95.75	3.07	90.70
	S2B2	71	444	192.76	97.68			
	S2B3	71	191	192.14	97.37			
3	S3B1	83	773	202.69	102.64	102.57	2.71	97.99
	S3B2	83	1697	208.00	105.30			
	S3B3	83	393	204.59	103.59			
	S3B4	87	630	194.88	98.74			
4	S4B1	65	683	187.45	95.02	98.63	4.80	90.84
	S4B2	65	199	191.17	96.88			
	S4B3	65	346	205.39	103.99			
5	S5B1	505	309	199.59	101.09	102.04	3.04	96.93
	S5B2	505	354	199.60	101.10			
	S5B3	505	404	210.50	106.55			
	S5B5	512	558	196.25	99.42			
6	S6B1	89	212	250.33	126.46	123.49	5.13	113.06
	S6B2	89	239	256.80	129.70			
	S6B3	89	194	243.10	122.85			
	S6B5	113	966	227.32	114.96			
7	S7B1	210	495	243.81	123.20	114.78	6.08	103.30
	S7B2	210	256	213.20	107.90			
	S7B3	210	325	232.69	117.64			
	S7B4	219	413	218.14	110.37			

* Time between $P = 0$ and P_u , † Lower confidence limit: $LCL_{5\%}$ = Mean – 1.645 SD

it is possible that the beam is already close to its ultimate shear capacity and may fail during load application. This did not happen. In two cases shear failure was observed relatively shortly after reaching the maximum load: beam S4B6 failed 2.5 hours after the application of the sustained load and beam S7B6 44 hours after the application.
As the sustained loads were applied in a deformation-controlled way, corrections in time were necessary, such as due to relaxation of the concrete causing a reduction of the sustained load. Therefore, the load had to be adjusted to the desired level. A few times, changes in temperature of the room (due to maintenance) have caused a temporary increase or decrease of the sustained load. Moreover, some beams (S3B5, S4B4 and S4B5) had to be unloaded and reloaded due to maintenance of the test facilities.
The beams in Series 2 were tested 84 days under sustained loading. Subsequently, the beams were loaded to failure in order to evaluate the possible reduction of the shear resistance after 84 days. The duration of the sustained loading in the other series are also mentioned in the last column of Table 3.

Table 3. Beams tested under sustained loading

Series No.	$V_{u,\text{mean}}$	Label	Age at t_0	P_{sus}	$V_{\text{sus}} = \frac{1}{2}P_{\text{sus}} + \frac{1}{4}m_b\, g$	$\lambda = \frac{V_{\text{sus}}}{V_u}$	Description
	kN		day	kN	kN		
2	95.75	S2B4	72	165.1	83.85	0.88	Stopped after 84 days
		S2B5	72	165.1	83.85	0.88	Stopped after 84 days
		S2B6	72	165.1	83.85	0.88	Stopped after 84 days
3	102.57	S3B5	87	196.0	99.30	0.97	Stopped after 1344 d.
		S3B6	87	196.0	99.30	0.97	Stopped after 127 days
4	98.63	S4B4	71	185.0	93.80	0.95	Stopped after 274 days
		S4B5	71	185.0	93.80	0.95	Stopped after 274 days
		S4B6	71	190.5	96.55	0.98	Failed after 2.5 hours
5	102.04	S5B4	512	185.0	93.80	0.92	Stopped after 784 days
		S5B6	696	173.0	87.80	0.86	Stopped after 600 days
6	123.49	S6B4	113	224.0	113.30	0.92	Stopped after 1113 d.
		S6B6	113	224.0	113.30	0.92	Stopped after 1113 d.
7	114.78	S7B5	219	210.0	106.30	0.93	Stopped after 950 days
		S7B6	219	205.5	104.05	0.91	Failed after 44 hours

4.1 *Load intensity*

The goal was to keep the load intensity factor λ on each beam constant during the whole sustained loading time. However, as the concrete strength increases, the shear resistance of the beam is supposed to slightly increase as well and the real-time load intensity λ would become smaller than the initial value defined at t_0 . In the interim period, the load intensity factors as given in Table 3 are the values at the beginning of sustained loading (t_0). The value of the applied load is plotted for each beam in the figures 2-4.

4.2 *Time-dependent deflections*

Concrete when subjected to long-term sustained loading, is subjected to creep deformation. The creep deflection of a reinforced concrete beams under a sustained load depends on the

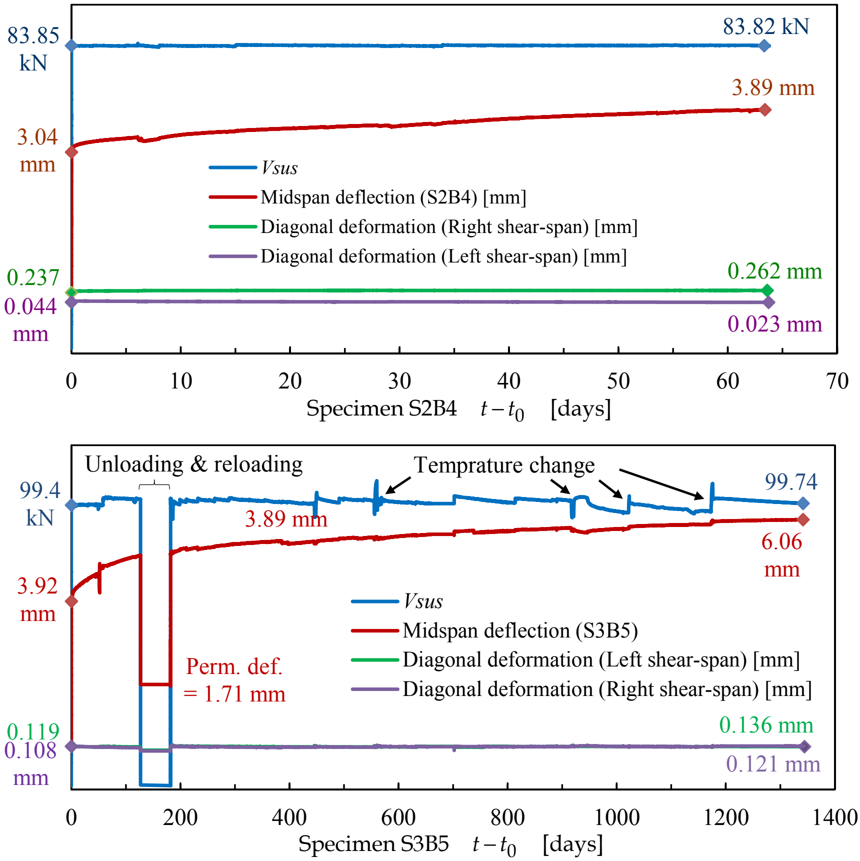


Figure 2. Sustained load, midspan deflection and diagonal deformations of S2B4 in 64 days and S3B5 in 1344 days

load intensity, the reinforcement ratio and the concrete properties (Table 1 and 3). The beams in Series 1-5 have the same reinforcement ratio, but the concrete strength and the load intensity of each beam is different. The creep deflection of the reinforced concrete beams at mid-span is plotted against time in the figures 2-4. Also the mid-span deflection right after load application at t_0 ($V = V_{sus}$) and at the end of sustained loading is given in each graph.

Furthermore, diagonal deformations at the right and the left shear spans, obtained through the two diagonal LVDT's (Fig. 1) are plotted in the same graphs. The measured values at t_0 and at the end of sustained loading indicate two types of behaviour:

- In a number of beams (S2B5, S3B5, S4B4, S4B5, S4B6, S5B6 and S7B6) both diagonal

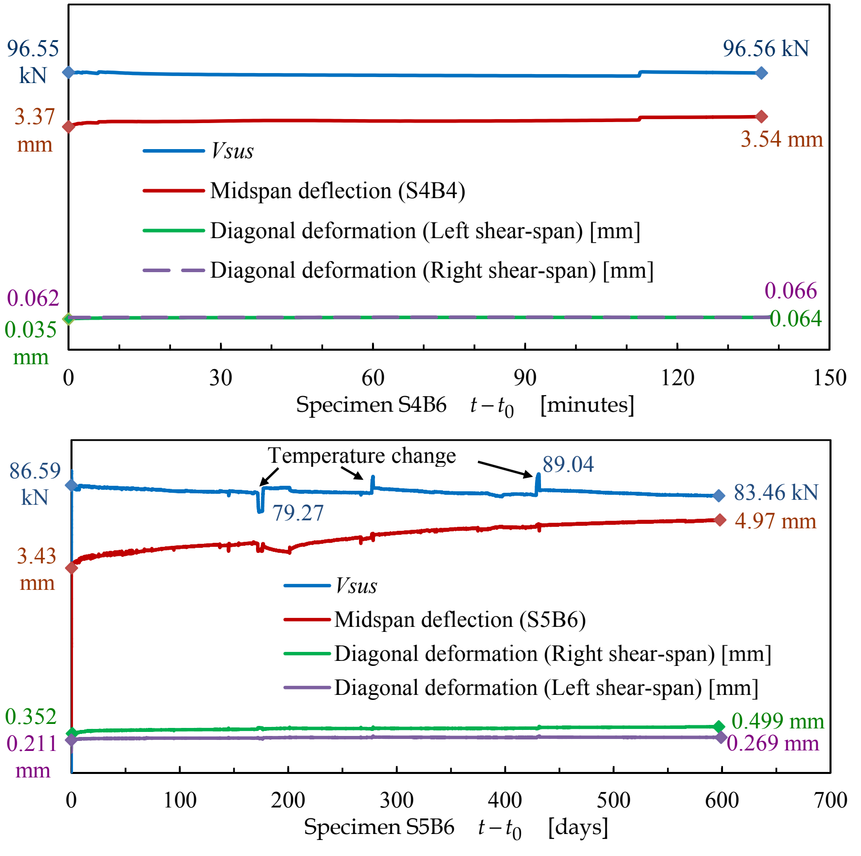


Figure 3. Sustained load, midspan deflection and diagonal deformations of S4B6 in 139 minutes and S5B6 in 600 days

deformations at the right and the left shear spans have increased in time, which is likely to cause further opening of the diagonal shear cracks in both spans.

- In some other beams (S2B4, S2B6, S3B6, S5B4, S6B4, S6B6 and S7B5) the diagonal deformation at one side (shear span) has been increased while at the other side (shear span) a slight decrease is observed. In this case, it is expected that the diagonal cracks have been mostly opened in the shear span with increasing diagonal deformation.

Nevertheless, in order to study the behaviour of diagonal shear cracks in time, special effort has been put in monitoring the crack width and crack length development, which will be presented later.

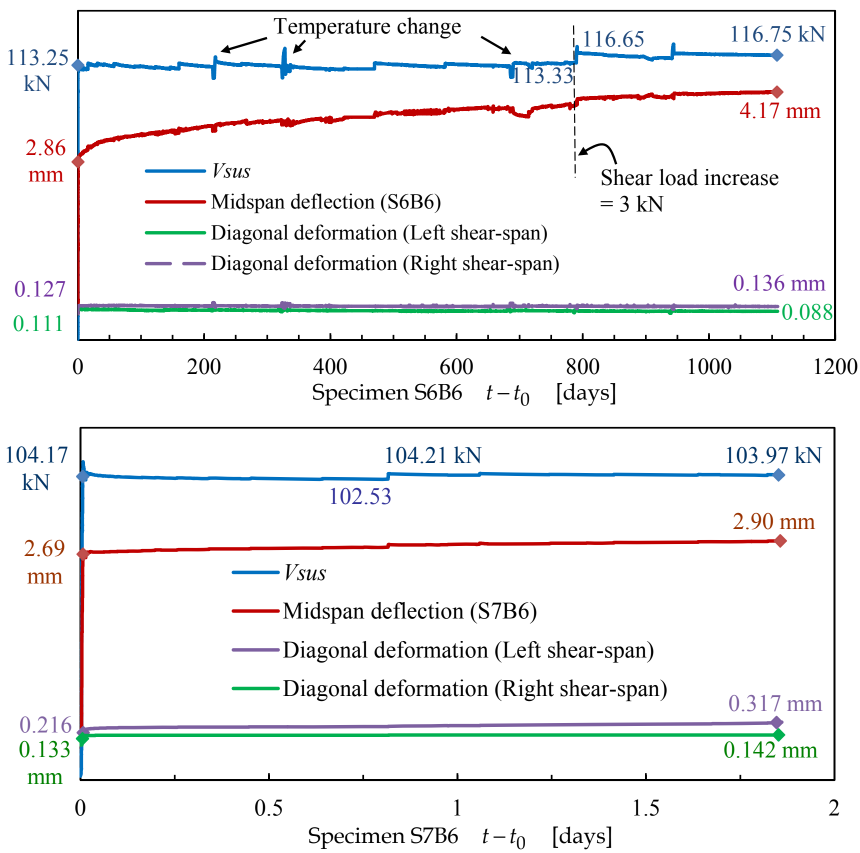


Figure 4. Sustained load, midspan deflection and diagonal deformations of S6B6 in 1113 days and S7B6 in 44 hours

4.3 *Crack pattern*

During the sustained loading tests, the surface crack pattern has been monitored and labelled at the surface of the beam. Monitoring of the cracks started just after loading ($t = t_0$). The most significant development of the crack pattern occurs during the first day of loading. As mentioned earlier, shrinkage cracks have been marked prior to sustained loading. However, concrete at an age of 70 days is still subjected to shrinkage and some of the cracks at the surface of the beams are likely to be short shrinkage cracks. The surface cracks of the RC beams under sustained loading are shown in Figure 5 to Fig. 8. The blue dashed line and the green lines with snaps at both ends represent the longitudinal reinforcement and the diagonal LVDT's, respectively.

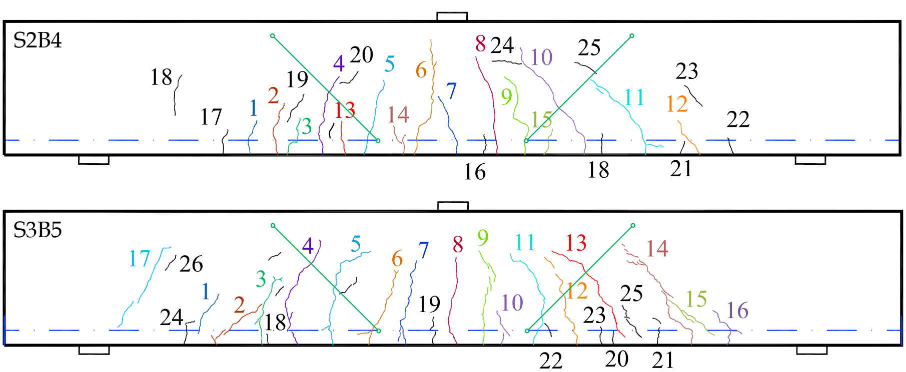


Figure 5. Crack pattern of specimens S2B4 after 84 days of sustained loading and S3B5 after 1344 days of sustained loading with crack numbers to be used in Figure 8

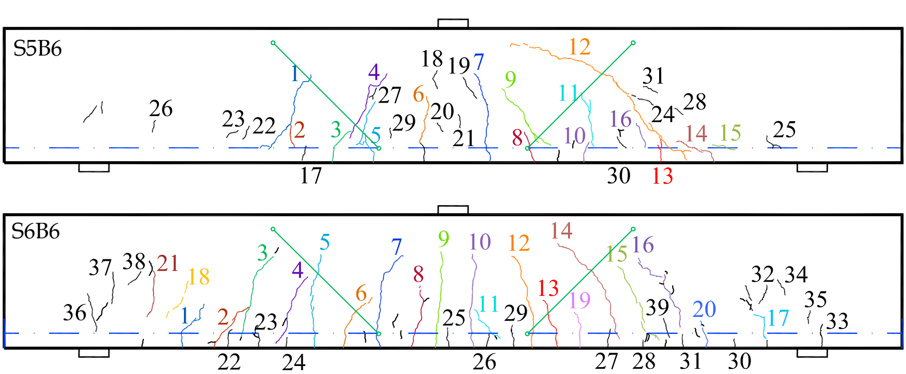


Figure 6. Crack pattern of specimens S5B6 after 600 days of sustained loading and S6B6 after 1113 days of sustained loading with crack numbers to be used in Figure 9

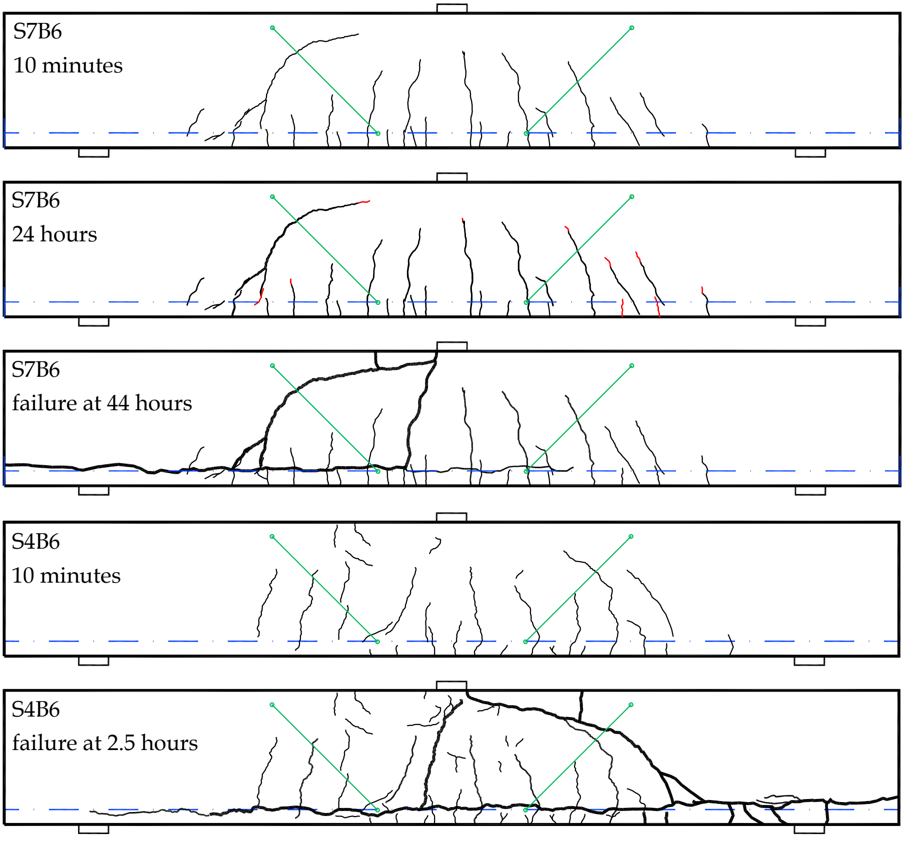


Figure 7. Crack pattern of specimens S4B6, which failed after 2.5 hours and S7B6, which failed after 44 hours

4.4 *Crack length development in time*

The surface crack pattern of the beams under sustained loading was presented in Figure 6. Most of these surface cracks appeared immediately after the application of the load at t_0, while some propagate in time and some others remain dormant. There are also some cracks that appear at the surface of the beam during sustained loading. All these cracks are numbered in the figures 5-7 and their length is marked and measured in time.

The results of crack length development are presented in the Figures 8 and 9. The surface cracks are categorized in two groups; major cracks and minor cracks. Minor cracks are denoted as short-length cracks (less than 100 mm) and it was inferred that short-length cracks have no influence upon shear (or flexural) failure: yet they are large enough to potentially affect the stress distribution in the beam. On the other hand, major cracks, that are identified to be longer than 100 mm, are expected to take part in the failure process of the beam.

It is evident from the Figures 8 and 9 that some of the surface cracks propagate in time, while some others stay dormant. The development of the crack length is not necessarily limited to the major cracks: sometimes the minor cracks show considerable progress, while there is no development in the major cracks.

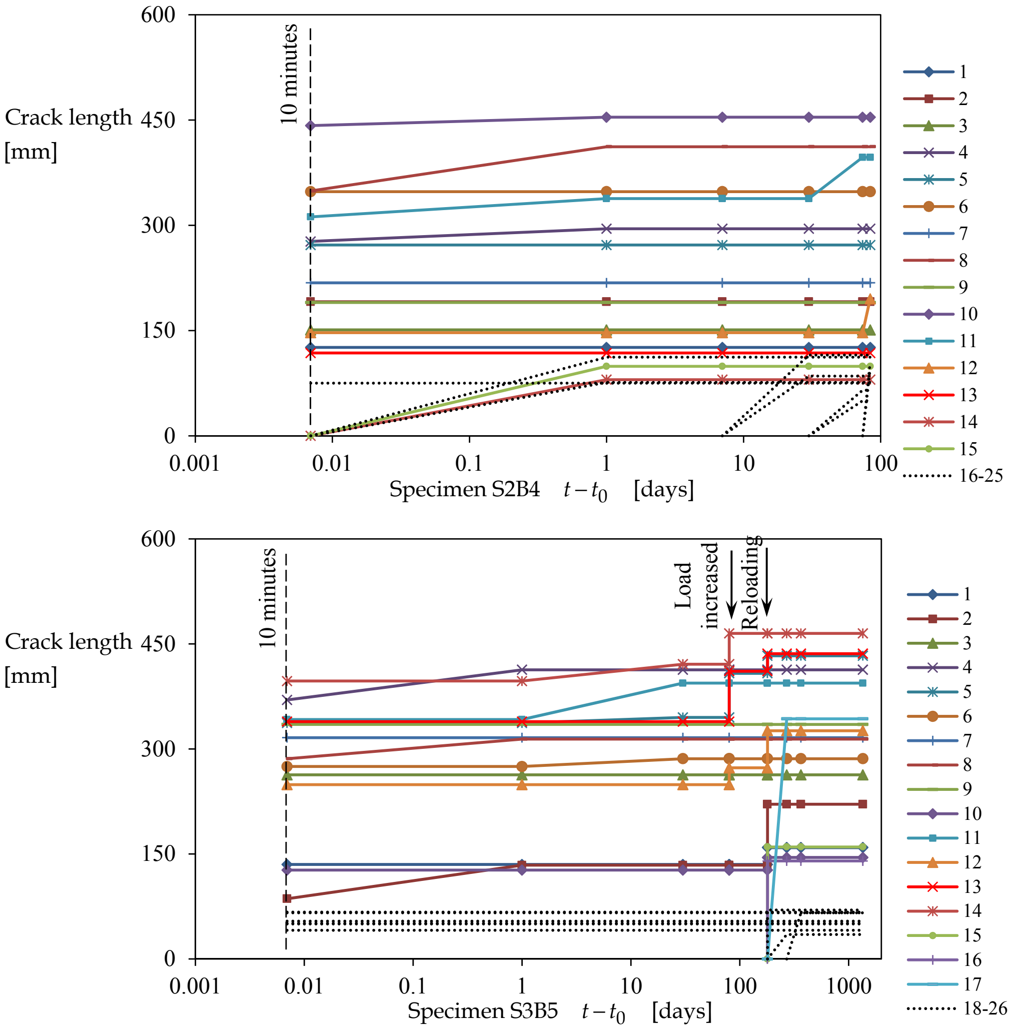


Figure 8. Crack length development of specimens S2B4 in 84 days under sustained loading (the crack numbers refer to Fig. 5) and S3B5 in 1344 days under sustained loading (the crack numbers refer to Fig. 5)

In order to minimize the effect of an increasing concrete strength (due to hydration of cement) during long-term loading, the beams have been loaded at an age of at least 70 days. However, a large number of new cracks have appeared at the beam surface during sustained loading that are likely to be shrinkage cracks. In view of that and for a better interpretation of the new cracks, two specimens (S5B4 and S5B6) have been loaded at the rather high concrete ages of 512 days and 696 days. A comparison between the results of the monitoring of the cracks in the fresh concrete and the old concrete (S5B4 and S5B6),

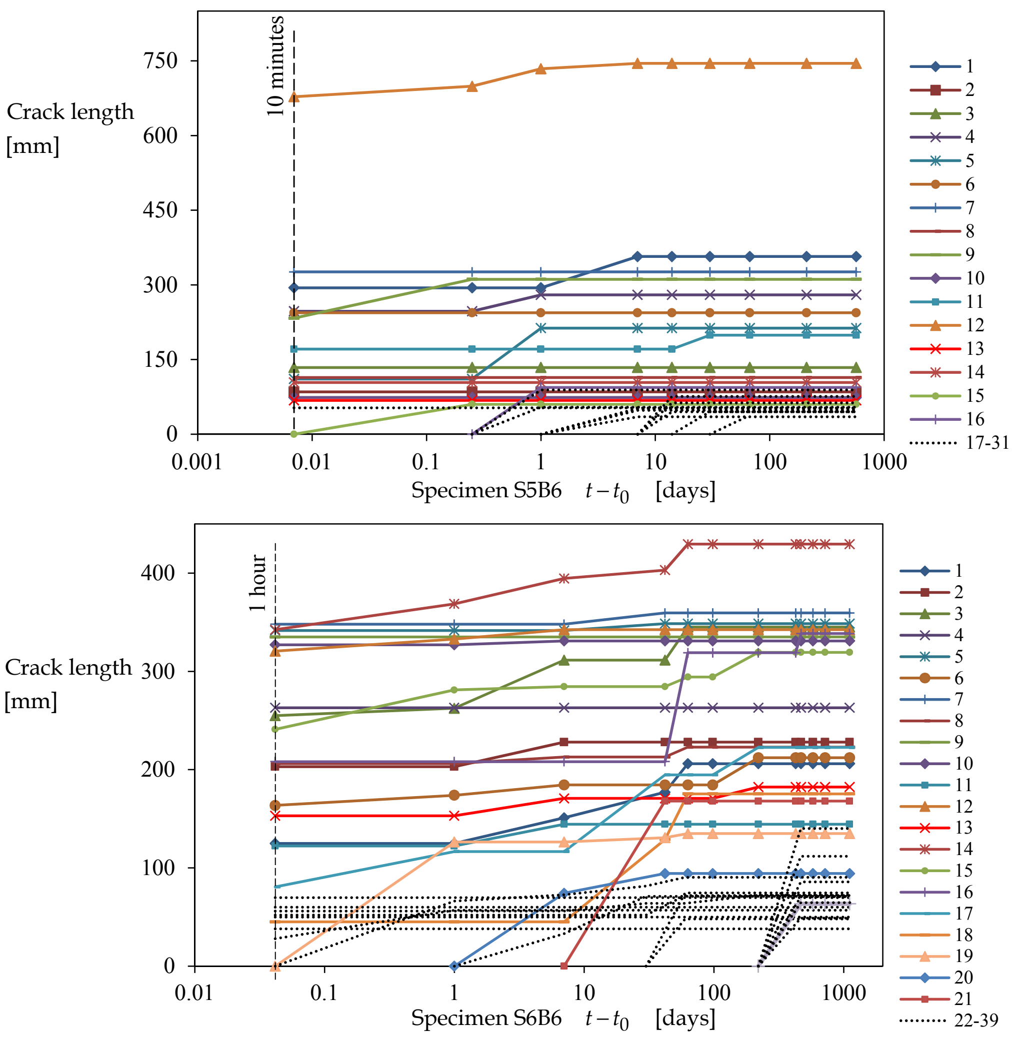


Figure 9. Crack length development of specimens S5B6 during 600 days under sustained loading and S6B6 during 1113 days under sustained loading

shows that most of the new cracks that develop during the long-term tests are shrinkage cracks, as the number of the new surface cracks during the sustained loading is significantly smaller in the old concrete beams. An important observation during the sustained loading is that the cracks do not propagate any more after 6 months ($t - t_0 > 180$ days) of sustained loading under constant conditions of temperature, humidity and external load.

4.5 ***Crack width development in time***

Crack width has its maximum value at the mouth of the crack and it reduces along the crack length to zero at the crack tip. In case of flexural cracks, the crack has its maximum opening at the bottom fiber. However, for an inclined shear crack, which opens in tension, the crack width is controlled by the reinforcement at the bottom and the maximal crack width can be measured at about the mid-height of the beam. In view of that and in order to determine the maximum opening of each crack, a measuring grid consisting of 241 lines and 96 points was required to cover the cracked surface of the beam.

For the major cracks at the surface of the beams, as explained earlier, a hand-operated manual LVDT device has been used in order to measure the width of cracks. This method has been used for the beams of Series 5-7.

As shown in Fig. 10, the development of crack width (measured at the widest part of each crack) is measured in time. Minor cracks have been neglected in this measurement. The development of crack width in time can be categorized into three cases:

- Some cracks such as Nr. 12 in S5B6 show a significant increase of crack width in time (52%). This refers usually to the longest shear cracks at the surface of the beam.
- Most of the cracks are dormant or demonstrate only a slight widening in time.
- A few cracks such as Nr. 5 in S6B6, show a reduction of crack width in time. It was inferred that due to stress redistribution in the beam, the stresses around these cracks were reduced and so has the crack width.

The ratio of the crack width at time t to the crack width at time t_0 was calculated as $w(t)/w(t_0)$ for every single crack. The development of average crack width, standard deviation and coefficient of variation are given in Table 4. The mean increase of crack

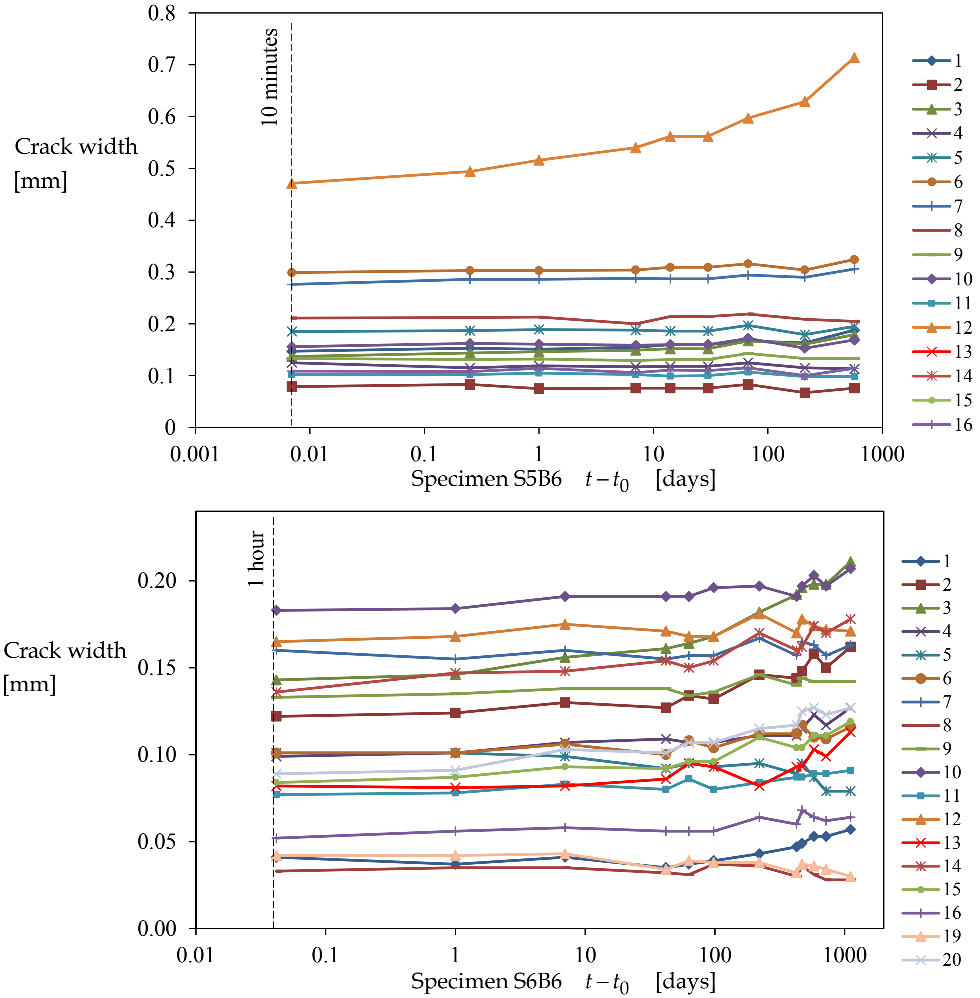


Figure 10. Development of crack width; Left: specimen S5B6 during 600 days under sustained loading. Right: specimen S6B6 during 1113 days under sustained loading. For the crack numbers reference is made to Figure 6

width in time is between 9.8% (S5B6) and 16.1% (S6B6) with a maximum individual increase of crack width of 53%. It should be noted that the sustained loading time was not the same for the various beams considered.

In Table 4, the ratio of midspan deflection Δ at time t to the midspan deflection Δ at time t_0 is given. A comparison to the rates of crack width development and development of the midspan deflection in the tested beams shows that the development of crack width in time is much smaller than the evolution of the midspan deflection in time, but it appears as well that there is a correlation between them.

Table 4. Development of average crack width in time and evolution of midspan deflection

Specimen	$f_{c\text{,cube, 28 days}}$	$t - t_0$ *	$\frac{\Delta(t)}{\Delta(t_0)} - 1$		$\frac{w(t)}{w(t_0)} - 1$	
	MPa	days		Mean	SD	COV
S5B4	44.1	784	0.346	0.135	0.228	0.201
S5B6	44.1	600	0.291	0.098	0.172	0.157
S6B4	81.2	1113	0.387	0.130	0.123	0.109
S6B6	81.2	1113	0.461	0.161	0.226	0.195
S7B5	80.7	949	0.289	0.134	0.202	0.179

*In this table t_0 is the time at which the first measurement of crack width has been conducted, which is usually 10 minutes or 1 hour after load application

*4.6 **Stress redistribution in time***

In order to investigate the stress redistribution in the beam during a sustained loading test, the elongation of the lowest row of the measuring grid, which is installed at the same height as the reinforcement, has been monitored in time. The distance between the preinstalled reference points has been measured before the load application and frequently during sustained loading. The plots in Figure 11 illustrate the displacement between the reference points along the reinforcement for beam S6B6. A reduction of the distance between the reference points in time has been marked with a green arrow: a red arrow has been used for an increase of the distance between the reference points.
It is seen that the local maxima of the curves increase in time and the local minima decrease. It is generally inferred that any increase in the spacing of two reference points due to crack opening, has been matched by a decrease in the spacing of the adjacent two reference points that reduces the corresponding crack width.

*4.7 **Shear resistance of RC beams after sustained loading***

In order to assess the effect of sustained loading on the shear resistance of reinforced concrete beams, the concrete beams have been loaded to failure at the end of the period of sustained loading. Cube compressive strength tests have been performed in time together with the beam tests to get insight into the concrete strength development. Based on the

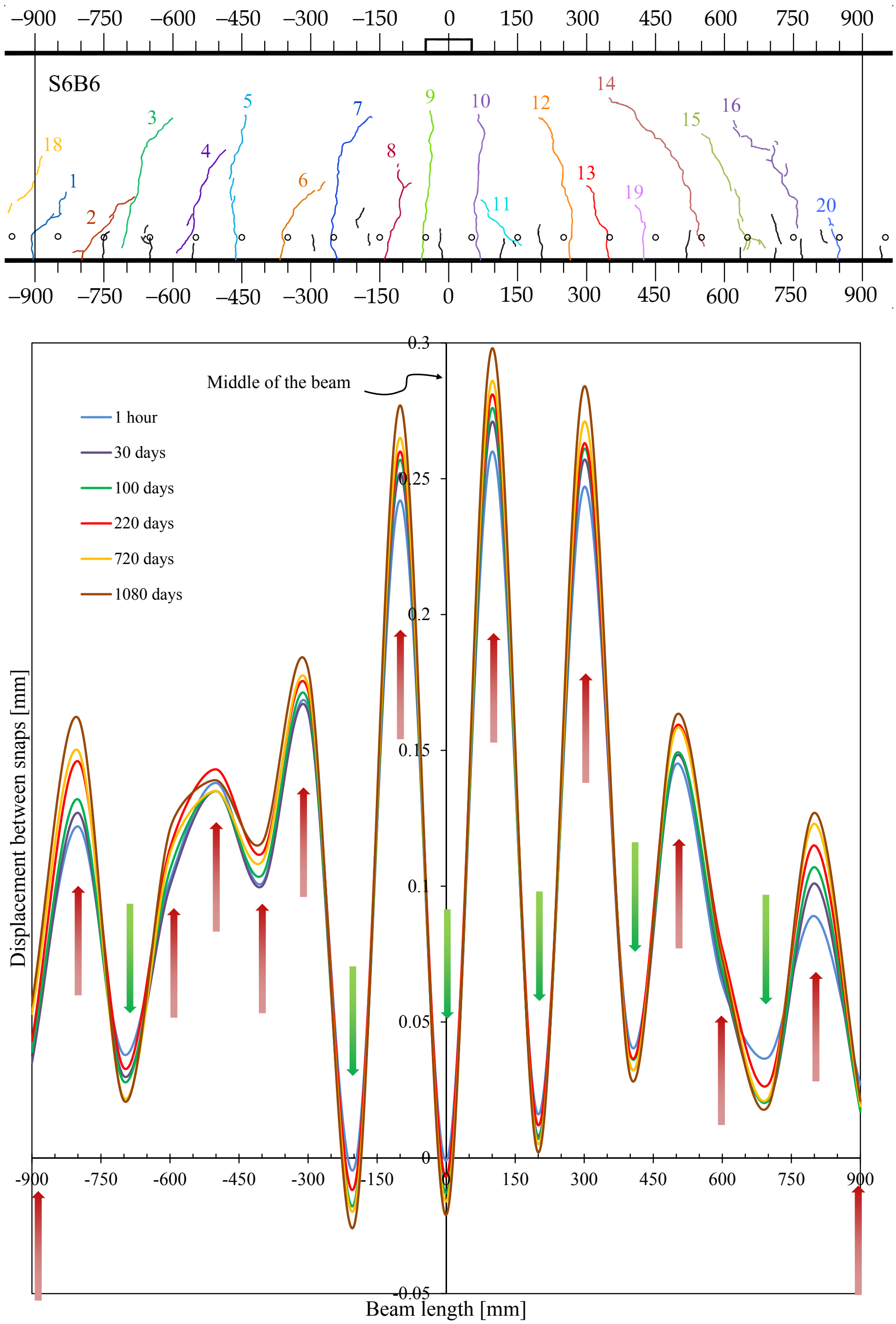


Figure 11. Displacement between measuring reference points at the reinforcement level; specimen S6B6 in 1080 days under sustained loading

compressive strength of the concrete, the shear resistance $V_{u,\text{calc}}$ of the beams has been recalculated in time according to the following equation (EN 1992-1-1)

$$V_{Rd,c} = C_{Rd,c} \sqrt[3]{100\,\rho_l f_{ck}}\, b\, d \tag{1}$$

where ρ_l is the longitudinal reinforcement ratio, f_{ck} characteristic concrete cylinder compressive strength. b is the width of the specimen and d is the effective depth of the cross-section $C_{Rd,c}$ is the coefficient which is 0,12 for the design equation and 0,15 for determining the mean shear resistance

Following the expressions of Eurocode 2, given Table 3.1 of EN 1992-1-1, 1 the shear resistance of the beam at a time t may be corrected by:

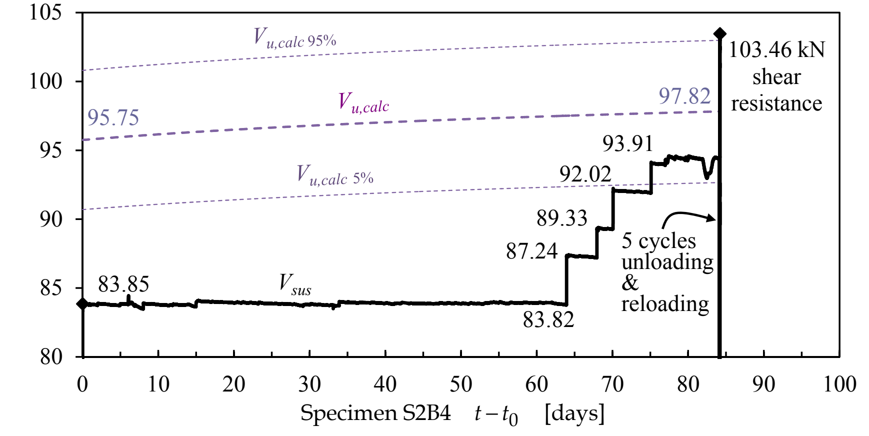
$$V_{u,\text{calc}}(t) = V_{u,\text{mean}}(t_0)\sqrt[3]{\frac{f_{cm}(t)-8}{f_{cm}(t_0)-8}} \tag{2}$$

The results are shown in Fig. 12 and 13. In these graphs, a comparison has been made between the shear resistance after sustained loading and the calculated shear resistance of the beam $V_{u,\text{calc}}$ with respect to the short-term shear resistance $V_{u,\text{mean}}$ and real-time concrete strength. The following observations were made:

- The sustained load on specimen S2B4 after 64 days has been increased step-by-step in order to exceed the characteristic value (lower confidence limit $V_{u,\text{calc }5\%}$). After any load increment, the load was kept constant for 4-6 days, see Figure 12. At an age of 84 days, the specimen has been subjected to five cycles of unloading and reloading, nevertheless no failure occurred. Subsequently, the load has been increased to failure. The shear resistance was found to be 103.46 kN, which corresponds with the 95% fractile of the calculated shear resistance $V_{u,\text{calc }95\%}$ according to the real-time concrete strength.
- Specimen S3B5 has been unloaded after 127 days because of maintenance reasons and reloaded 60 days later to 101.6 kN, see Figure 12. The sustained loading has been ended after 1344 days and subsequently the load has been increased to failure. The shear resistance was found to be 113.22 kN, which corresponds with the 95% fractile of the calculated (theoretical) shear resistance $V_{u,\text{calc }95\%}$ according to the real-time concrete strength.
- The sustained load on specimen S5B6 after 600 days has been increased to failure, see Figure 13. The shear resistance was found to be 97.17 kN, which is equal to the

characteristic value of the calculated shear resistance $V_{u,\text{calc 5\%}}$. Also the sustained load on specimen S6B6 after 1113 days has been increased to failure (Fig. 13, right). The shear resistance was found to be 148.68 kN, which is higher than the 95% fractile value of the calculated shear resistance.

A summary of the shear resistances after long-term loading is given in Table 5. It is evident that the shear resistance of the beams $V_{u,\text{exp}}$, which had been previously loaded under



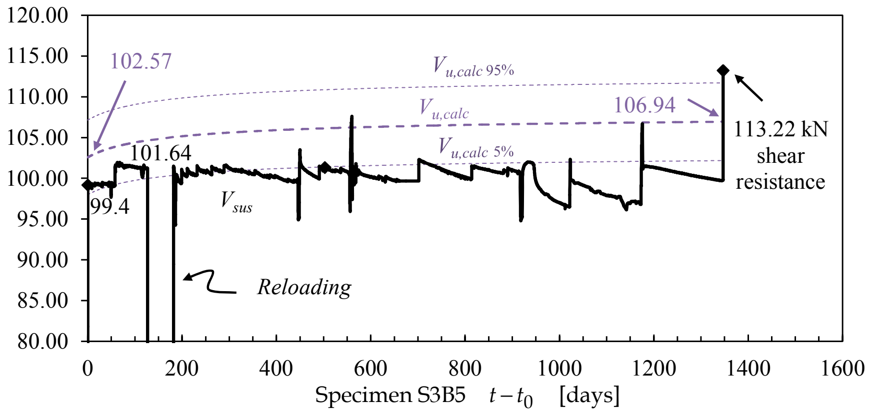


Figure 12. Left: Shear resistance of S2B4 at the end of sustained loading and comparison with the calculated shear resistance $V_{u,\text{calc}}$ according to the real-time concrete strength. Five cycles unloading and reloading were conducted at V_{sus} = 93.9 kN. Right: Shear resistance of S3B5 at the end of sustained loading and comparison with the calculated shear resistance $V_{u,\text{calc}}$ according to the real-time concrete strength.

high sustained loads (load intensity over 0.86), is generally higher than the theoretically calculated shear resistance $V_{u,\mathrm{calc}}$ at time t.

From Table 5 it can be concluded that the probability to find an increase of the shear resistance after sustained loading is 83.2%, see Figure 14. This is most probably due to stress relaxation in the concrete especially around the crack tip. In other words, the static shear resistance of the beams was hardly affected by the load history of the specimens.

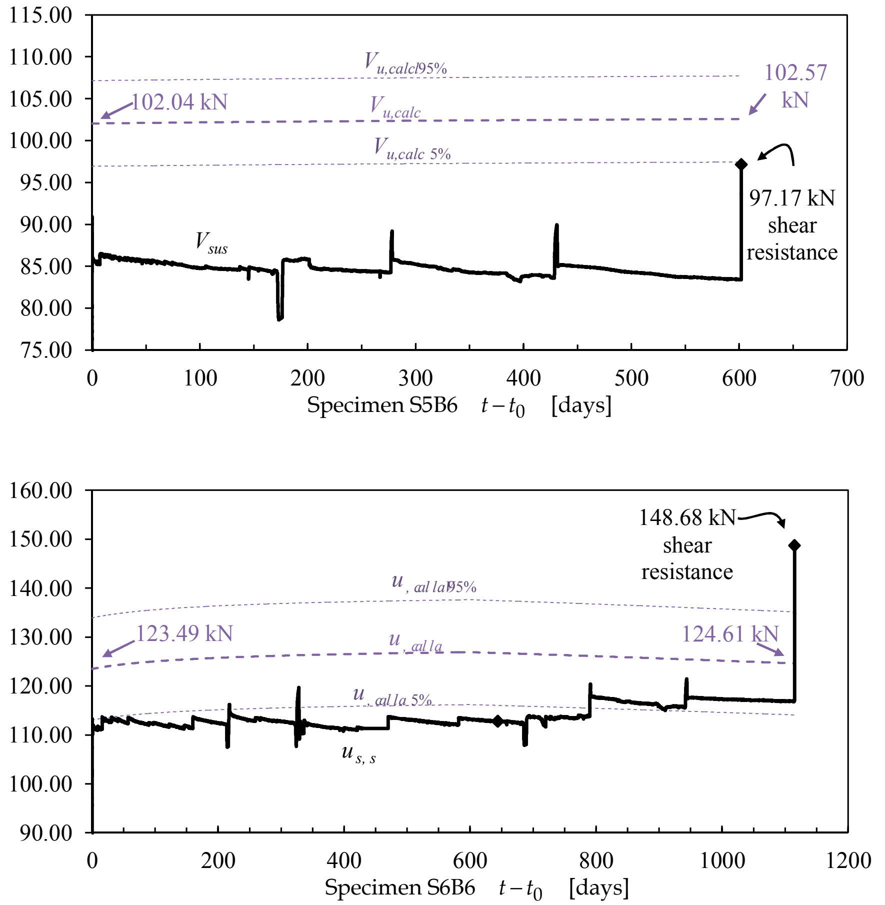


Figure 13. Left: Shear resistance of S5B6 at the end of sustained loading and comparison with the calculated shear resistance $V_{u,\mathrm{calc}}$ according to the real-time concrete strength. Right: Shear resistance of S6B6 at the end of sustained loading and comparison with the calculated shear resistance $V_{u,\mathrm{calc}}$ according to the real-time concrete strength.

Table 5. Shear resistance at the end of long-term sustained loading

Specimen	t_0	t	$f_{cm,\text{cube}}(t_0)$	$f_{cm,\text{cube}}(t)$	$V_{u,mean}(t_0)$	$V_{u,\text{calc}}(t)$	$V_{u,\text{exp}}$	$\frac{V_{u,\text{exp}}}{V_{u,\text{calc}}(t)}$
	days	days	MPa	MPa	kN	kN	kN	
S2B4	72	156	39.5	41.6	95.75	97.82	103.46	1.06
S2B5	72	156	39.5	41.6	95.75	97.82	102.51	1.05
S2B6	72	156	39.5	41.6	95.75	97.82	105.03	1.07
S3B5	87	1431	51.8	57.7	102.57	106.94	113.22	1.06
S3B6	87	214	51.8	54.5	102.57	104.65	100.85	0.96
S4B4	71	345	51.0	55.6	98.63	102.00	116.40	1.14
S4B5	71	345	51.0	55.6	98.63	102.00	118.42	1.16
S5B4	512	1296	55.7	56.9	102.04	102.90	116.41	1.13
S5B6	696	1296	56.2	56.9	102.04	102.57	97.17	0.95
S6B6	113	1226	90.7	92.7	123.49	124.61	148.68	1.19
						Average		1.08
						SD		0.080
						COV		0.074

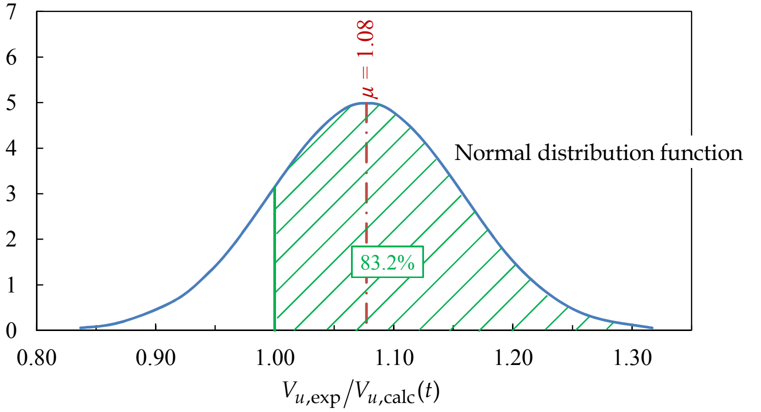


Figure 14. Normal distribution function of the ratio of the experimental shear resistance $V_{u,\text{exp}}$ to the calculated shear resistance $V_{u,\text{calc}}$

5 Summary with most important observations

A brief summary of testing concrete beams without shear reinforcement under long-term sustained loading can be drawn as follows:

- Long-term sustained loading tests have been conducted on large-scale concrete beams with load intensities between 0.86 and 0.98, for periods between 2.5 hours and 1344 days.
- During sustained loading, the surface cracks propagate in time. However, after 6 months ($t - t_0$ > 180 days) of sustained loading under constant conditions of temperature, humidity and external load, no crack length development has been observed anymore.
- The measurement of the crack width shows that the width of some cracks increases under sustained loading, while some other cracks are dormant or even show a slight reduction in width. Still, the average width of the cracks increases in time as the concrete beam deforms due to the creep effect.
- The stress redistribution in time causes the opening of some cracks, while some other cracks show a reduction of the crack width.
- In order to find out the effect of sustained loading on the shear resistance of reinforced concrete beams, the concrete beams have been loaded to failure at the end of the period of sustained loading. Based on the expected development of the compressive strength of concrete, the shear resistance $V_{u,\mathrm{calc}}$ of the beams has been recalculated in time.
- A comparison has been made between the calculated shear resistance of the beam $V_{u,\mathrm{calc}}$ according to the real-time concrete strength and the shear resistance determined experimentally after the period of sustained loading. No negative effect of the previous sustained loading has been observed: on the contrary, a statistical evolution of the results shows that the expectation of an increase in shear resistance after sustained loading is 83%.
- Altogether 42 tests have been conducted on shear-critical reinforced concrete beams without stirrups. Amongst them, 28 beams have been tested under monotonic short-term loading as reference tests and 14 beams have been tested under long-term sustained loading. The results of short-term monotonic tests with the purpose of identifying the shear resistance show a relatively small scatter of V_u in the same series with a coefficient of variation below 6.48%. The mean value of the shear resistance

$V_{u,\text{mean}}$ in each series has been used as the reference value for the shear resistance of the same series when testing under long-term loading.

- Long-term sustained loading tests have been carried out on fourteen shear-critical concrete beams with longitudinal reinforcement at the tensile side and without stirrups. The beams had cube concrete strengths of 34.6 MPa to 81.2 MPa in the different series and have been subjected to sustained loads with load intensities ($\lambda = V_{\text{sys}}/V_{u,\text{mean}}$) over 0.86, for a period between 2.5 hours and 1344 days. The goal was to study the behaviour of shear cracks under a high level of sustained loading, close to the short-term shear resistance. During the long-term sustained loading tests, the crack width development, the crack length development and the appearance of new cracks have been monitored.
- Results of an investigation into the surface crack length development during long-term sustained loading showed that the surface cracks did not propagate any more after 6 months ($t-t_0$ > 180 days) of sustained loading under constant conditions of temperature, humidity and external load. However, the crack width measurements show that the average width of the cracks increased in time as the concrete beam deformed due to the creep effect.
- Stress redistribution in the reinforced concrete beams occurred in time. Any increase in the crack width, correspond with a decrease in the stress of the adjacent concrete parts between the cracks.
- At the end of the period of long-term loading, the concrete beams have been tested to failure. No negative effect of the previous sustained loading has been observed as the shear resistance of the tested beams appeared to be generally higher than the calculated shear resistance $V_{u,\text{calc}}$ with respect to the short-term shear resistance $V_{u,\text{mean}}$ taking into account the increase of the concrete strength in time.

6 Conclusions

1. The sustained loading effect, which is well known to apply for concrete subjected to axial compression or axial tension, does not apply to the shear resistance of structural concrete members without shear reinforcement, although this resistance is formulated as a function of the concrete strength.
2. The residual shear resistance of existing solid slab bridges without shear reinforcement, determined using the strength results of drilled cores, needs not to be reduced by a sustained loading factor.

3. The explanation for the absence of the sustained loading factor should be based on improved modelling of the shear carrying behavior. This is treated in a follow-up paper (Sarkhosh et al., 2016)

References

[1] Sarkhosh, R., "*Shear resistance of reinforced concrete beams without shear reinforcement under sustained loading*", PhD thesis, Delft University of Technology, the Netherlands, April 17th 2014.

[2] EN-1992-1-1 "Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings"

[3] *fib* Model Code for Concrete Structures 2010, Ernst & Sohn, 22013

[4] Sarkhosh, A., Walraven, J.C., den Uijl. J.A., "Shear critical reinforced concrete beams under sustained loading – Part II: Numerical study", *HERON* Volume 60 (2015) No. 3 pp. 207-234