# Shear Capacity of Concrete Beams under Sustained Loading

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## Summary

Long-term tests on large-scale concrete beams without shear reinforcement, which are tested for more than two years under sustained loading close to the ultimate shear capacity (load ratio ranging from 87% to 95%) under climate controlled condition, show that sustained loading has no significant effect on the shear capacity. Although many flexural and shear cracks develop, the beams carry the load for a long time. The tests show that crack formation takes place only within some days after the load application, but after a week the cracks stabilize and become dormant.

**Keywords:** Shear capacity, Concrete beams, Sustained loading, Time effect.

## 1. Introduction

The design and construction of concrete bridges systems with long-term durability is a significant challenge for bridge engineers. Another challenging topic was and still is the failure behaviour of concrete slabs and concrete beams (or slab strips) without shear reinforcement. Yet little attention has been paid to the behaviour of shear cracks under long-term sustained loading. The effect of sustained loading has been investigated by some researchers [1-6] on plain concrete in tension and bending. According to Zhang et al. [6], in a bending test on plain concrete, the sustained stress follows a semi-logarithmic or exponential relationship in time. However, lack of experimental data has led to uncertainty of using a reduction factor for concrete strength in case of sustained loading. This factor should be used to account for the long-term versus the short-term concrete tensile strength and is evaluated based on the long-term behaviour of plain concrete loaded in tension.

According to the Dutch Code for Concrete Structures [7], the concrete strength under long-term loading is 0,85 of the short-term strength. Since shear resistance is a function of the tensile strength of concrete, also this aspect is then subjected to a sustained loading effect.

In the Eurocode 2 [8], in case of sustained loading, the values of the design compressive strength $f_{cd}$ and design tensile strength $f_{ctd}$ are defined as:

$$\begin{aligned} f_{cd} &= \alpha_{cc} \cdot f_{ck} / \gamma_c \qquad (compression) \\ f_{ctd} &= \alpha_{ct} \cdot f_{ctk,0.05} / \gamma_c \qquad (tension) \end{aligned} \tag{1}$$

where, $f_{ck}$ and $f_{ctk\,0,05}$ are the characteristic compressive strength and characteristic axial tensile strength respectively, $\alpha_{cc}$ is the coefficient taking account of long-term effects on the compressive strength and of unfavourable effects resulting from the way the load is applied and $\gamma_c$ is the partial safety factor for concrete, which is 1,50 for both compression and tension. The value of the sustained loading factor ($\alpha_{cc}$) may be assumed between 0,8 and 1. However, for normal density concrete the sustained loading factor is defined to be 1.

The goal of this research is to predict the time-dependent mechanical behaviour of concrete beams without shear reinforcement subjected to sustained loading and to quantify the possible shear capacity loss due to long-term loading. For that reason, a series of tests are carried out on concrete beams subjected to high shear loads close to the short-term failure load, for periods ranging from 90 days to 1000 days, during which the deflection, crack lengths, crack widths and appearance of the new cracks in time, are monitored periodically (e.g. at $t = 1$ hour, 1 day, 7 days, 30 days, etc).

## 2. Background

When a concrete beam is under high sustained loading, a flexural and shear crack pattern appears along the span. This crack pattern is similar to the crack pattern in case of short-term loading, but the cracks are not wide/long enough to let the fracture occur. Here, various shear-carrying mechanisms may be developed by a beam, e.g. aggregate-interlock and dowel action. These mechanisms induce tensile stresses in the concrete near the crack tip and at the level of the reinforcement. Once the tensile strength of the concrete in these regions is reached, existing flexural cracks propagate in a diagonal direction or new ones are created. The development of the shear/flexural crack, however, does not necessarily imply the collapse of the member but in case of high sustained loading, the crack length and therefore the crack width increase in time.

Experimental investigations show that the fracture process in concrete structures includes three different phases: crack initiation, stable crack propagation and unstable crack propagation that results in failure [9]. In order to predict the crack propagation, vaious fracture models, like the fictitious crack model by Hillerborg et al. [10] and the effective crack model by Karihaloo and Nallathambi [4] have been proposed. In the models, different material parameters are introduced to describe the cracking properties of concrete materials. These fracture models that attempt to adapt LEFM to concrete structures can only be used to predict the unstable fracture (i.e. in front of crack tip) and cannot be used to predict crack initiation.

Zhou [5] proposed a time-dependent fracture model for concrete based on experimental tests on pre-notched concrete beams. The experimental procedure is based on two segments. In the first segment, the external load grows from zero to the nominal level (a fraction of the maximum load $P_{max}$) under deflection control. During the second segment, the load is kept constant until creep rupture occurs. Such tests are usually denoted as pre-peak sustained bending tests. Of course, in order to know the maximum load $P_{max}$, static tests have to be executed previously. To overcome this difficulty, researchers prefer to use the so-called deformation-controlled post-peak tests where the creep phase starts beyond the peak load [11].

## 3. Experimental tests on concrete beams

18 concrete beams (subdivided into 6 groups; groups 2-7, see Table 1) are tested under long-term sustained loading. Together with these beams, 24 extra beams are tested under short-term loading, in order to acquire the reference ultimate shear capacity, crack opening displacement (COD), type of failure, and to gain insight into the scatter of the results. The beams are reinforced longitudinally at the bottom to prevent bending failure. No shear reinforcement is used. To provide sufficient anchorage capacity, steel plates are welded to both ends of the bars. The geometry of the beams and the loading setup are shown in Fig. 1. The compressive strength, ultimate capacity $P_{max}$ (short-term) and load ratio (long-term load as a percentage of the short-term ultimate capacity $P_{max}$) are shown in Table 1.

The measuring system installed on each beam consists of a load-cell, one vertical LVDT at midspan to measure deflection and two diagonal LVDT's to measure the diagonal deflections and shear crack opening displacement (COD) in short-time (see Fig1.Right). An additional measuring system with a manually operated LVDT is applied on beams in groups 5, 6 and 7. Zero measurements are taken when the beams are only loaded by their self-weight. Thus, the influence of the self-weight is not

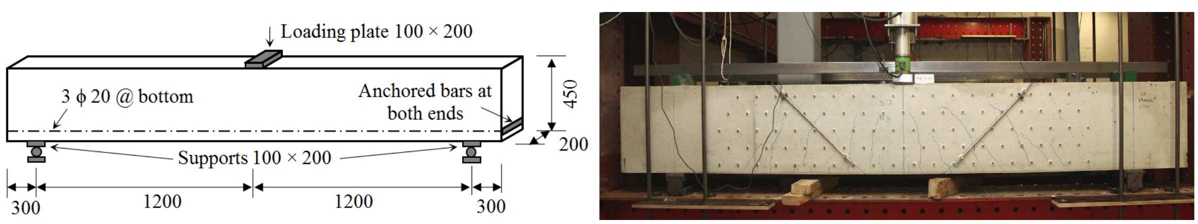


*Fig. 1: Left: Geometry of the beams. Right: Measuring devices installed on the beam*

incorporated in the measuring results of the LVDT's. After 28 days curing in a fog room (99% RH, 20 ºC), beams are stored and tested in a climate room at 50% RH and 20 ºC.

*Table 1: Specimens in short-term (ST) and long-term (LT) loading*

| Group | $f_{c,cube,\ 28\ days}$ (MPa) | ST Specimen label | $P_{max,\ mean}$ (kN) | LT Specimen label | Concrete age at $t$ = 0 (days) | Load ratio (%) | Loading time $t$ (days) |
|---|---|---|---|---|---|---|---|
| 1 | 38,1 | G1B1-G1B6 | 184,7 (cov = 4,6%) | *All six specimens are tested in short-term loading* | | | |
| 2 | 32,1 | G2B1 | 188,9 (cov = 3,2%) | G2B4 | 70 | 87 | 97 |
| | | G2B2 | | G2B5 | 70 | 87 | 97 |
| | | G2B3 | | G2B6 | 70 | 87 | 97 |
| 3 | 47,0 | G3B1 | 204,9 (cov = 1,4%) | G3B4 | 85 | 95 (failed) | – |
| | | G3B2 | | G3B5* | 85 | 95 | >1000 |
| | | G3B3 | | G3B6 | 85 | 95 | 130 |
| 4 | 42,0 | G4B1 | 194,7 (cov = 4,9%) | G4B4 | 70 | 95 | 315 |
| | | G4B2 | | G4B5 | 70 | 95 | 352 |
| | | G4B3 | | G4B6† | 70 | 95 | 1/10 |
| 5 | 44,2 | G5B1 | 203,2 (cov = 3,1%) | G5B4* | 500 | 91 | >500 |
| | | G5B2 | | G5B5 | 500 | 94 (failed) | – |
| | | G5B3 | | G5B6* | 710 | 81 | >300 |
| 6 | 73,4 | G6B1 | 250,1 (cov = 2,7%) | G6B4* | 110 | 90 | >800 |
| | | G6B2 | | G6B5 | 110 | 88 (failed) | – |
| | | G6B3 | | G6B6* | 110 | 90 | >800 |
| 7 | 78,0 | G7B1 | 229,9 (cov = 6,7%) | G7B4 | 215 | 95 (failed) | – |
| | | G7B2 | | G7B5* | 215 | 92 | >700 |
| | | G7B3 | | G7B6† | 215 | 87 | 2 |

* Specimens those are still under sustained loading

† Specimens those are failed under sustained loading

### 3.1 Short-term loading

In the short-term tests, P-COD curves are obtained for the reference beams. The COD's in Fig. 2 are related to the failure cracks and are measured along two diagonal LVDT's that are installed on the surface of the beam, see Fig. 1. The diagonal LVDT's have a measuring length of 40 cm and may cover several cracks.

In short-term tests, upon the growth of the crack to the compression zone, the beam fails by crushing of the concrete compressive-zone. This occurs before the tension zone reinforcement yields, which does not provide any warning as the fracture is instantaneous. The ultimate load $P_{max}$ is considered to be the highest peak in the $P$-$\delta$ curve. The value of $P_{max}$ in Table 1 is the mean value of three beam tests with the same concrete mix, tested in short-term loading.

Two types of failure are observed in the short-term tests. Both are flexural shear failure, but Type I is characterized by a shear crack crossing the potential compression strut and Type II is failure due to a crack not crossing the potential compression strut which is mostly associated with a relatively higher ultimate load, see Fig. 3.

Specimens G2B2, G3B2, G4B1 and G4B2 show Type II failure which has a large midspan

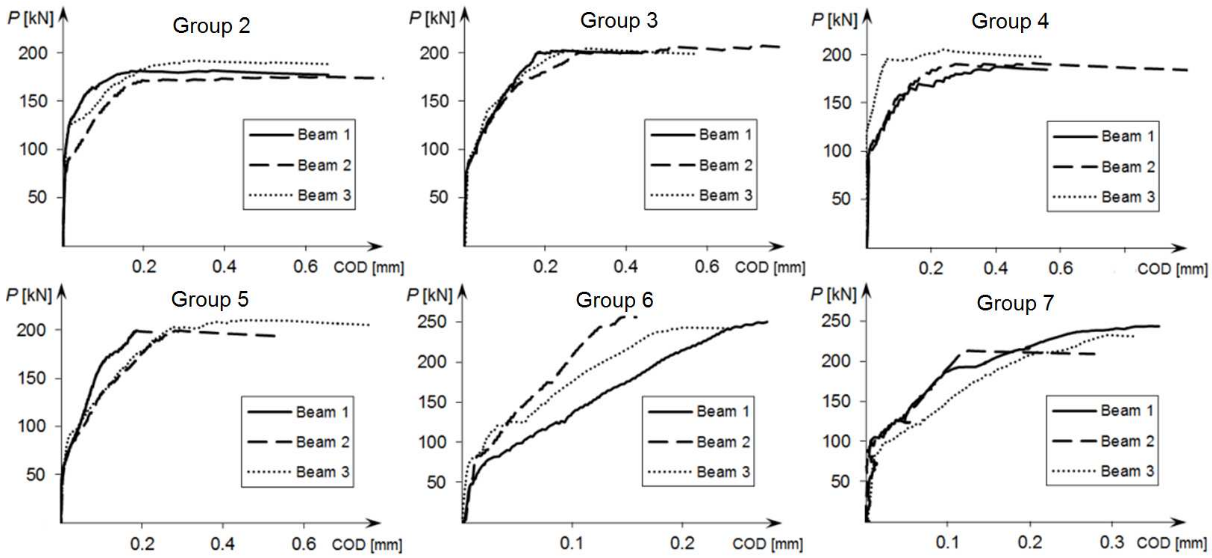

*Fig. 2: P-COD curves in short-term tests*

deflection and a large crack opening displacement. The reason to have a larger deflection and a larger crack opening than with the first failure type is that the crack tip ends under the loading plate and the confining action by the loading plate prevents the crack tip to open. However, more deflection leads to larger crack opening at the middle of the crack. The rest of the beams fail according to Type I, which involves instantaneous fracture of the beam.

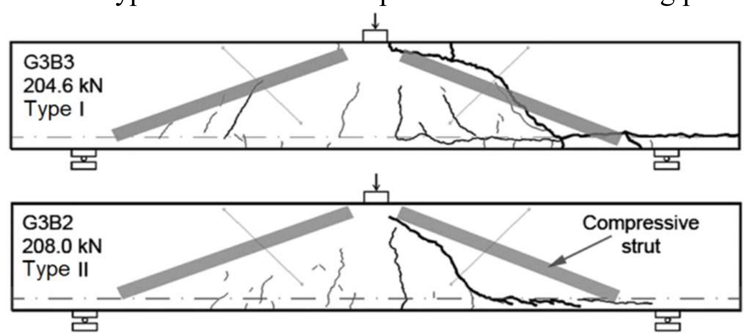

*Fig. 3: Types of failure*

### 3.2 Long-term loading

As described in Table 1, the concrete beams are subjected to long term loading for a period between 3 months and 3 years. The goal is to study the behaviour of wide and long shear cracks under high sustained loading, which is at a load close to the ultimate shear capacity. A load ratio between 87% and 95% of the $P_{max,\ mean}$ (see Table 1) is applied to the beams. Undeniably, in case of high load ratio (when the load is within the 95% interval of $P_{max}$), the risk of failure during application of the load increases as the load ratio increases. In some cases (specimens G3B4, G5B5, G6B6 and G7B4) beam fails before reaching the desired load level. During the long-term loading tests, the crack opening development, the crack length development and the appearance of new cracks are monitored.

#### 3.2.1 Crack length in time

The progress of every single crack on the surface of the beam is monitored in time. The surface cracks are categorized into two types; major cracks and minor cracks. Minor cracks are called to very short cracks (less than 100 mm length) those may never cause the failure or be part of a failure crack, but are large enough (longer than 10 mm) to potentially affect the stress redistribution in the beam. In order to avoid the development of shrinkage cracks in time, the concrete beams are tested at an age of 70 days or more. However, the results show that most of the new cracks that develop during the test are shrinkage cracks. This will be explained in detail in section 3.2.3.

Fig. 4 shows the crack length development in time. Clearly, some of the cracks grow in time, while some have a dormant length. Growth of crack length is not necessarily limited to the large cracks; sometimes small cracks show considerable progress, while there is no progress in the large cracks.

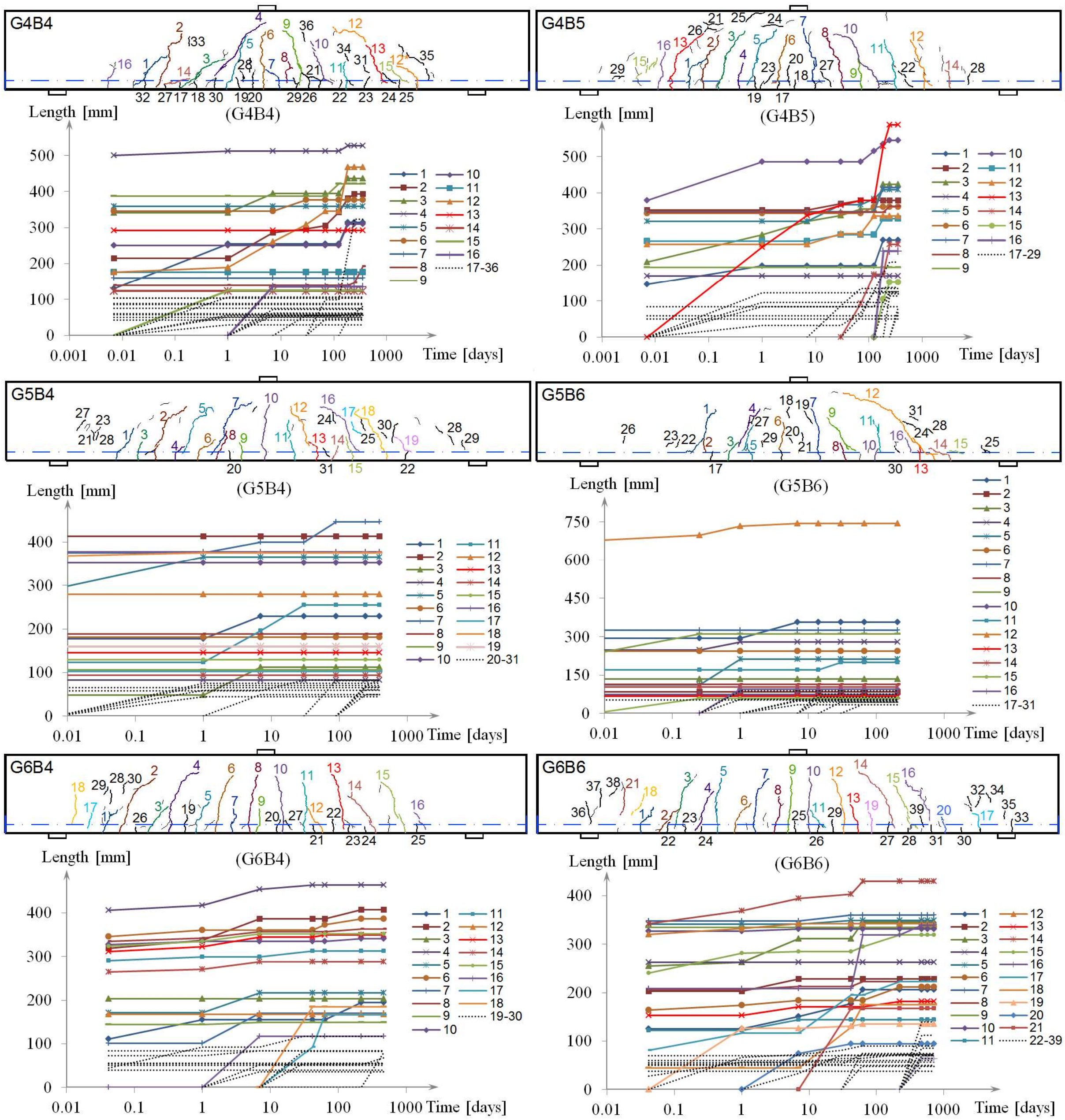

*Fig. 4: Development of crack length in time*

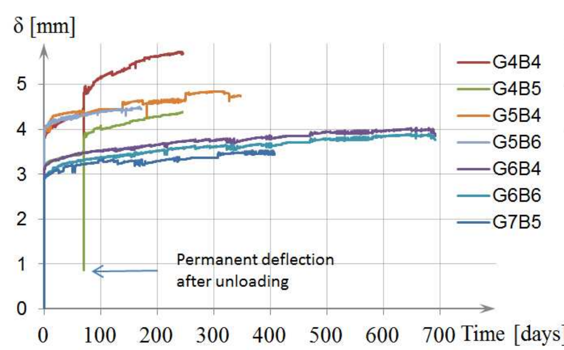

*Fig. 5: Midspan deflections in time*

The increasing length of cracks in specimens G4B4 and G4B5 after 145 days are caused by step-by-step increase of load ratio. A comparison to the crack length development in G5B4 and G5B6 with old concrete (500 days and 710 days old at $t = 0$) and crack length development in specimens with fresh concrete (less than three months old; specimens G4B4, G4B5, G6B4 and G6B6), demonstrates that the crack development in these old beams is less than in fresh beams. Fig. 4 shows that there is a limit to the crack length development. Another observation during the long-term tests is that the cracks do not propagate after 6 months of loading. It should be mentioned that, during the long-term tests, some beams were unloaded and reloaded for some maintenance in the setups, which causes extra deformation (see Fig. 5) and therefore extra crack length development.

### 3.2.2 Crack opening in time

The width of a single crack on the surface of a beam has its maximum at the mouth of the crack and it reduces along the crack length to zero at the crack tip. In order to find out the maximum crack opening displacement, the crack width is measured perpendicular to the crack face at several locations along the crack length by means of a hand-operated LVDT and pre-installed measuring points on the surface of the beam. In Fig. 6, the COD of the major cracks is presented during sustained loading. Minor cracks are neglected to be measured, since most of them appear out of the measuring region. Noticeably, in some cracks, COD increases in time while in some other cracks it remains constant. The cracks with a considerable increase in length present a significant opening in time (e.g. crack number 3 in specimen G6B6, see Figs. 4 and 5). However, the results of periodically monitoring of the beams show that there are always some cracks those grow in length, but demonstrate a small change in width. The same happens with the opening of some cracks in time, but without any visible increase in length.

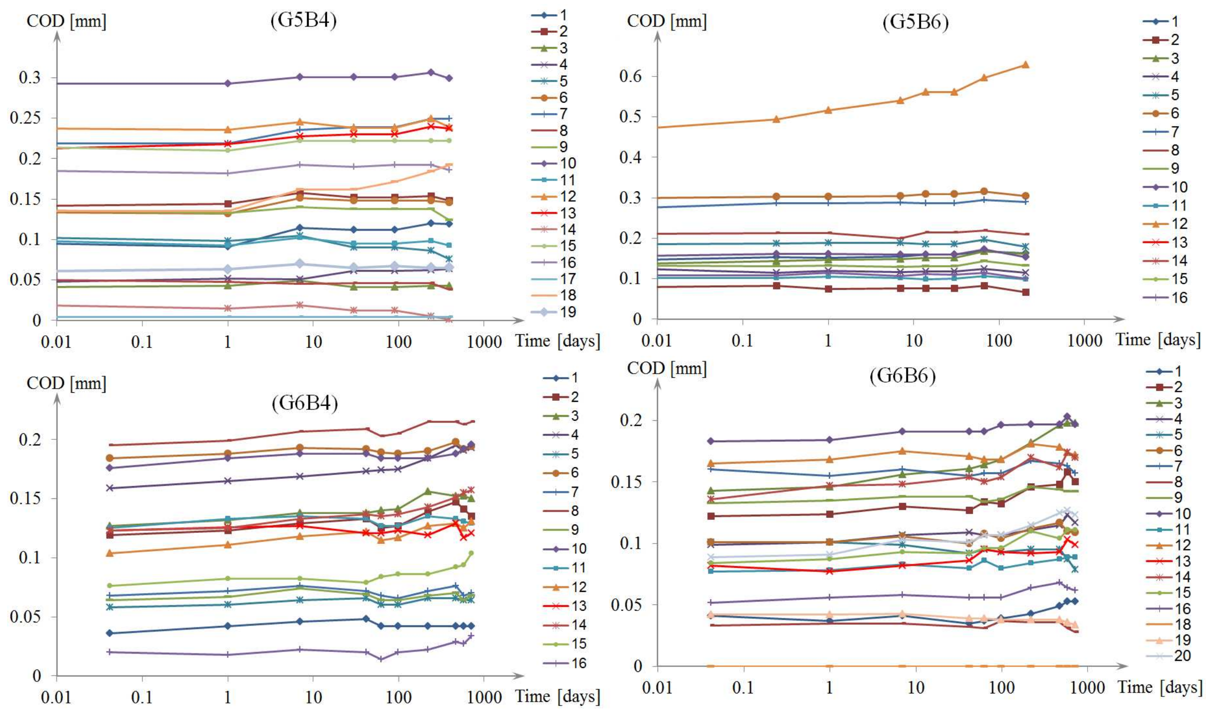


*Fig. 6: Development of crack width in time. Crack numbers are related to the beams in Fig. 4.*

### 3.2.3 Appearance of new cracks

A comparison between aged concrete specimens (G5B4 and G5B6) and fresh concrete beams (G4B4, G4B5, G6B4 and G6B6) shows that the development and appearance of new cracks, which are observed in periodically monitoring of the beams, are more visible in fresh concrete beams while in old concrete beams, the new cracks are rare to appear. It can be concluded that, most of the new cracks, which appear in time, are shrinkage cracks. It has also been observed that shortly after loading, the crack pattern is mostly developed in the middle of the beam, while after some time new cracks appear closer to the supports.

### 3.2.4 Ultimate shear capacity

In order to find out the effect of sustained loading (any possible reduction in capacity of the beam), beams in group 2 (G2B4, G2B5 and G2B6) are loaded to failure at the end of sustained loading period. Cube compressive strength tests were performed in time together with the beam tests to get insight into the concrete strength development. After 75 days of sustained loading (age of concrete

= 145 days), the loading ratio is adjusted to 90% of the actual strength, which is calculated according to the actual cube compressive strength. The load ratio is kept at 90% for 5 days, and then it is increased to 92,5%. This procedure continues until failure of the beam. In Fig. 8, the results of these tests are presented. Evidently, the ultimate shear capacity of the beams at the end of sustained loading corresponds to the estimated shear capacity (calculated numerically) and no effect of the previous sustained loading is detected.

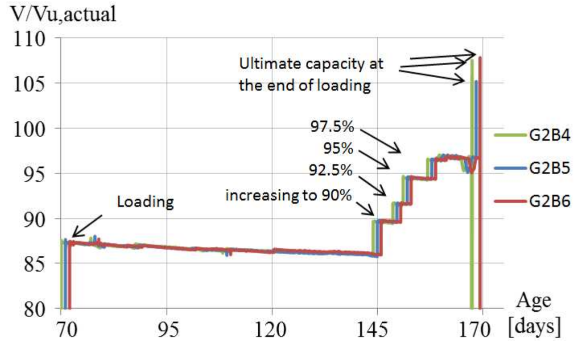


*Fig. 7: Relative load in time and ultimate capacity at the end of sustained loading*

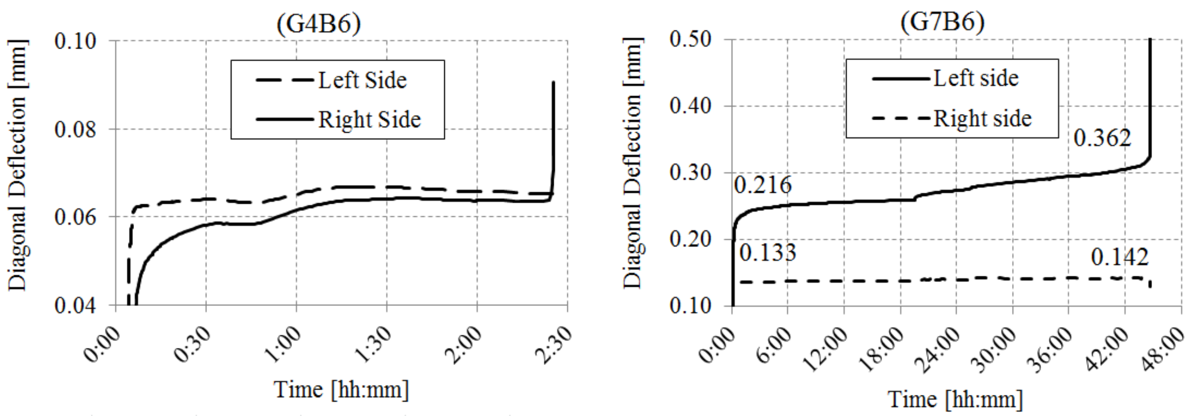


*Fig. 8: Fracture of two specimens shortly after application of sustained loading*

3.2.5 Failure of the beams shortly after initial sustained loading

As presented in Table 1, due to the reckless growth of the shear crack, specimens G4B6 and G7B6 failed under sustained loading of 185 kN (95% $P_{max,\ mean,\ group\ 4}$) and 200 kN (87% $P_{max,\ mean,\ group\ 7}$) respectively. The beams failed shortly after initial loading, when they were still in the crack initiation phase. Sustained loading time of specimen G4B6 was almost 145 minutes (1/10 day) and specimen G7B6 failed after 45 hrs, see Fig. 8 (Right). As shown in Fig. 8 (left), the COD at both sides of the beam are stabilized after 1.5 hour, but suddenly, when the load was still constant, the shear crack on the right side opened and the beam failed (see Fig. 9). Crack propagation and failure phase of G7B6 is shown in Fig. 10.

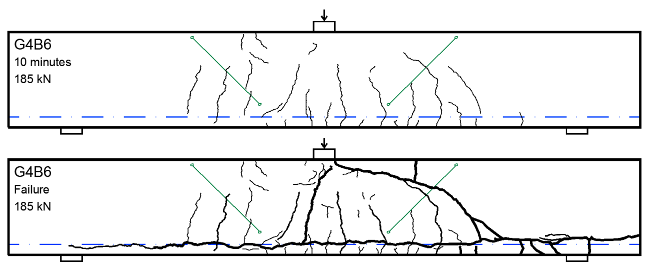


*Fig. 9: Failure of G4B6 after 145 minutes*

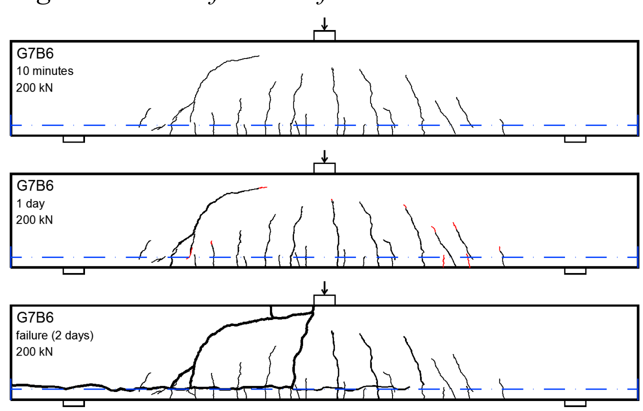


*Fig. 10: Failure of G7B6 after 45 hrs*

## 4. Conclusions

The following conclusions can be drawn from this research:

Shear tests are carried out on concrete beams without shear reinforcement, subject to high levels of loading. The level of the sustained loading corresponds to 87% – 95% of the average short-term shear capacity, which is determined in separate tests. The width and length of the cracks are monitored periodically. The tests do not show a significant sustained loading effect.

During sustained loading slight propagation of shear cracks is observed. This crack propagation is more pronounced in the first six months of loading. Furthermore, the results of monitoring the crack opening displacement in time show that the crack widths increase in the first week of loading, but afterwards the cracks stabilize and become dormant. Only one crack (crack nr. 12) in specimen G5B6 is still opening in time (Fig. 6), but after 220 days of sustained loading, no signs of failure are detected. It should be noticed that this crack had nearly 0,5 mm width at $t = 0$.

As drawn in 3.2.1, development of the crack length becomes dormant after a few months of sustained loading (in these tests between 3 and 6 months) and the cracks do not propagate anymore, indicating that there is limit to the crack length under constant sustained loading. A similar conclusion can be drawn for the width of the cracks, which become dormant after 1 week, indicating that there is also a limit to the crack width opening under sustained loading. Moreover, most of the new cracks appear on the beam are likely shrinkage cracks, as explained in 3.2.3.

In two cases shear failure occurred under sustained load: in one case 2,4 hours after loading and in the other case 44 hours after loading. In those cases, however, the sustained load was in the 95% confidence interval of the short-term shear capacity. The specimens in Table 1 marked with an asterisk (*) next to the label, are still under sustained loading. For further extensions of the sustained loading results described in this work, numerical investigation is required.

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