Development of a Smart Key Performance Indicator for In-Situ Load Tests

Dieteren, G; Bigaj-van Vliet, Agnieszka; Yang, Yuguang; Sangers, A

DOI
10.1007/978-3-319-59471-2_218

Publication date
2018

Document Version
Final published version

Published in
High Tech Concrete: Where Technology and Engineering Meet

Citation (APA)
Dieteren, G., Bigaj-van Vliet, A., Yang, Y., & Sangers, A. (2018). Development of a Smart Key Performance Indicator for In-Situ Load Tests. In D. Hordijk, & M. Lukovic (Eds.), *High Tech Concrete: Where Technology and Engineering Meet: Proceedings of the 2017 fib Symposium, held in Maastricht, The Netherlands, June 12–14, 2017* (pp. 1907-1916) https://doi.org/10.1007/978-3-319-59471-2_218

Development of a Smart Key Performance Indicator for In-Situ Load Tests

Gerrie Dieteren[1(✉)], Agnieszka Bigaj van Vliet[1], Yuguang Yang[2], and Alex Sangers[1]

[1] Structural Reliability, TNO, P.O. Box 49, 2600 AA Delft, The Netherlands
gerrie.dieteren@tno.nl

[2] Civil Engineering and Geosciences, Department Structural Engineering, Technical University Delft, P.O. Box 5048, 2600 GA Delft, The Netherlands
Yuguang.Yang@tudelft.nl

Abstract. In-situ load testing of reinforced concrete (RC) structures is often performed to confirm the presence of the required resistance for the intended use (Conformity Load Testing) or to support the assessments of the residual capacity by models (Supplementary Load Testing for Condition Assessment). When performing an in-situ load test, one of the main concerns is the avoidance of irreversible damage to the structure, since that may impair the structural performance after testing and eventually reduce its residual service life. Therefore performance indicator are needed to recognize the development and/or to prevent failure during an in-situ load test of real structures. For many of the existing RC structures without transverse reinforcement, shear failure is one of the governing mechanisms. Due to its brittle character, this failure mode is difficult to sense at an early stage of its development. Up to now no good performance indicator is available for shear. In the presented study, a smart key performance indicator for in-situ load tests has been developed, with particular focus on shear failure. Results of several laboratory tests on full- scale shear beams have been examined, confirming that a change in structural behaviour at an early stage during testing can be traced by the proposed indicator. With the proposed performance indicator, performing measurements only on the top or bottom of the tested specimen is necessary, which is of importance for the applications to existing structures, with limited access for measurements. An algorithm for data analysis has been developed, which can be used to control the proposed performance indicator in real time during testing.

Keywords: Key performance indicators · Proof load testing · Shear

1 Introduction

Many reinforced concrete bridges in the Netherlands have been built in the period 1930–1970 which means that they have reached a lifetime of 85–45 years. Many of these bridges were not designed for the current traffic load (traffic intensity and load

D.A. Hordijk and M. Luković (eds.), *High Tech Concrete: Where Technology and Engineering Meet*, DOI 10.1007/978-3-319-59471-2_218

level) and according to the current durability requirements. Infrastructure owners therefore are concerned whether these bridges fulfill the requirements with respect to structural safety, taking into account the likelihood of reinforcement corrosion or other types of degradation in combination with the increased traffic load. To be able to determine the current reliability level of RC bridges and to predict the reliability evolution in future, TNO had started an ERP-SI[1] research program, focussing on the assessment, forecasting and monitoring of the integrity of existing RC bridges subject to degradation due to reinforcement corrosion.

2 Load Testing

In general two types of in-situ load testing can be applied:

- Conformity Load Testing, which is a self-supporting alternative to condition assessment by models, and it is used to confirm the presence of the required resistance for the intended use, also known as proof load testing. Hence, the load applied during Conformity Load Testing to prove the required safety level is determined based on the intended use, taking into account all uncertainties on the loading and the resistance side.
- Supplementary Load Testing for Condition Assessment, which is applied to support condition assessments by models, with an objective of assessing the actual residual capacity of the structure, also known as diagnostic load testing. In a Supplementary Load Testing the applied load level may be lower than in Conformity Load Testing since testing is intended to provide information for improvement of the actual assessment model of the structure, thus reducing the modelling uncertainties. In the ongoing ERP-SI research program it is intended to enable improvement of condition assessment by combining predictive modelling with the Supplementary in-situ Load Testing and with other (non-destructive) testing of the structure.

Although in a Supplementary Load Testing the applied load level may be lower than that in a Conformity Load Testing, in both cases a chance that irreversible damage may occur during testing exists. Yet, irreversible damage during testing has to be avoided, since that may impair the structural performance and eventually reduce its residual service life. For many of the RC structures without transverse reinforcement, shear failure is one of the governing mechanisms. Due to its brittle character, shear failure is difficult to sense at an early stage of its development. Up to now, no good performance indicator is available to recognize the development and/or to prevent shear failure during an load test of real structures [ACI 2014, DAFStb 2000]. In the presented study, a smart key performance indicator for in-situ load tests has been developed.

[1] ERP-SI: TNO Early Research Program – Structural Integrity, Use case Bridge.

3 Tests for Key Performance Indicator (KPI) Development

Most of the available tests on beams failing in shear are performed on new beams without any pre-damage. However, in a research program of the Dutch Ministry of Infrastructure and the Environment, TU Delft in corporation with TNO tested beams extracted from an existing 50 year old bridge. Additionally, similar newly casted beams were tested for comparison. For a detailed description of the beam tests reference is made to Yang (2010, 2014). Examination of the results from existing (pre-damaged) and new (undamaged) beams enabled investigation of the effect of damage on key performance indicators.

4 Experimental Set-Up

In the test series, the specimens are prismatic RC beams without shear reinforcement. They are simply supported with single point load. On one side of all beams, an array of linear variable displacement transducers (LVDT's) was attached as shown in Fig. 1 to monitor real-time deformations and crack development. The deflection of the beams was monitored by three LVDT's attached to a frame resting on top of the beam. A pre-programmed sequential loading procedure was adopted as shown in Fig. 2. Specific load levels were identified, taking into account well defined stages of the beam response, such as cracking of the concrete and yielding of the rebars. The interval between two load levels is constant. At each of the resulting levels, the load was cycled three times between a level of 5 kN and the target level. The load was increased at a constant rate and kept constant during 2 min in the first two cycles and 5 min in the last cycle. The displacement control was applied after non-stable (shear) cracking had initiated. The main reason for choosing this loading procedure was to investigate whether by real time monitoring of the structural response during the repeated load cycles, the onset of non-stable crack growth can be detected before major damage occurs to the beam. Such approach is suggested for proof load testing for the flexural behaviour of structures by [DAfStB 2000], but in case of shear failure its validity has not been demonstrated yet.

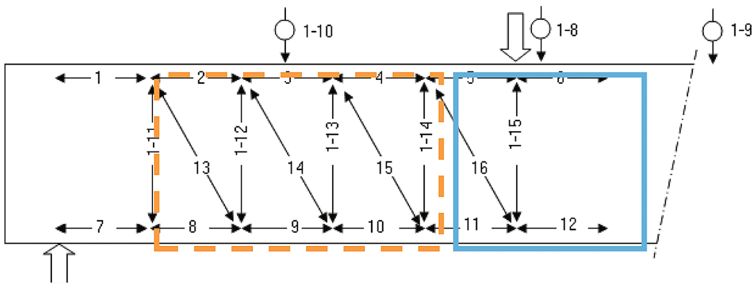

Fig. 1. The test setup of the specimen B10E1, LVDT sensors numbered. Blocks indicate the specimens shear zone (orange-dashed) and bending zone (blue).

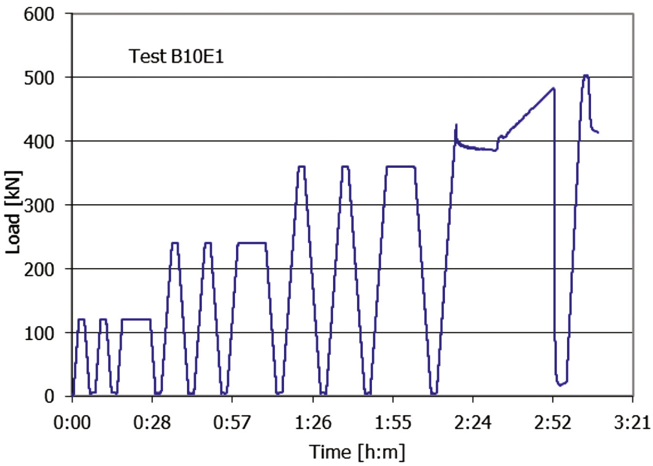

Fig. 2. Loading scheme of B10E1.

5 Evaluation of Key Performance Indicators

During laboratory tests or in-situ load tests, the measurement from LVDT sensors are often plotted against time or applied load. However, in practice these indicators do not perform well as real-time failure warning. To determine a suitable KPI in case of shear failure, firstly analysis were performed on beam B10E1 failing in shear. The following six different possible KPI's were analysed:

- KPI 1 Curvature
- KPI 2 Tangential stiffness
- KPI 3 Tension stiffening
- KPI 4 Strut deformation
- KPI 5 Ratio bending vs. shear curvature
- KPI 6 Ratio bending vs. shear tension stiffening

By combining the measurement results of several sensors, the resultant parameters reflect a certain structural aspect of the response in a certain region of the specimen (for instance curvature or tensions stiffening change). The distinguished regions were (i) bending zone were bending is governing, indicated as blue zone in Fig. 1) and (ii) shear zone (region in between the applied load and the support were shear is expected to be the governing mechanism, indicated as orange and dotted-line in Fig. 1).

6 KPI 1 Curvature

The curvature of the beam is defined according to $\kappa = (\varepsilon_{\text{tension}} - \varepsilon_{\text{compression}})/d$, where ε indicates the total strain in a specific location and d indicates the local height of the specimen. The curvature is determined based on the measurements with corresponding sensors placed at the bottom and top of the beam (for instance sensor 8–10 and 2–4 in

Fig. 1), and it is analysed both in shear and in bending zone. As long as no significant damage occurs, a linear behaviour to the applied load is expected, and for the applied loading set-up the curvature in the shear zone should be lower than the curvature in the bending zone.

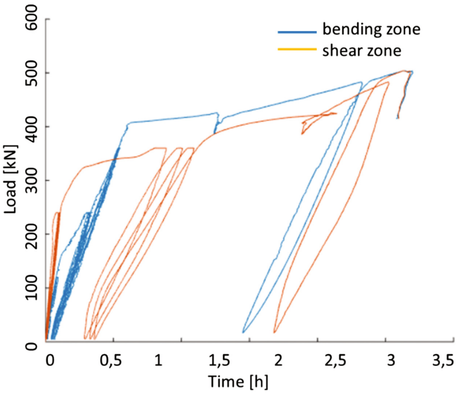

Fig. 3. Curvature in shear and bending zone with respect to the applied load in test B10E1.

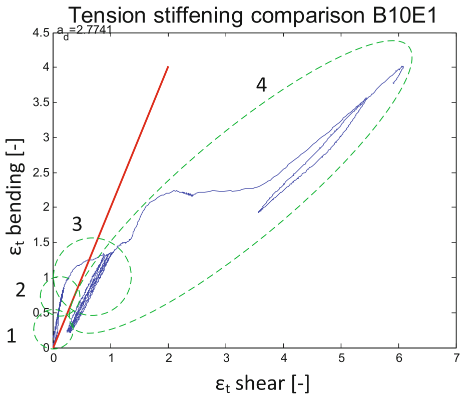

Fig. 4. The relation between curvature in the bending and shear zone, green circles correspond with the applied load step.

Figure 3 shows that at a load of approximate 340 kN (t = 1,3 h) this observation no longer holds true. At load step 3, in the shear zone repeated load steps do not show comparable behaviour with respect to curvature, which indicates that irreversible damage has occurred. Another way of presenting tests results with respect to curvature is given in Fig. 4. Here the relation between the curvature in both zones (bending and shear) is plotted, showing that at low load levels the curvature in the shear zone is linear with respect to that of the bending zone. The loading stage at which this linear relation seems to be lost is close to the stage at which the lines in Fig. 3 cross each other.

7 KPI 2 Tangential Stiffness

The tangential stiffness of the two zones is defined by dκ/dL with κ determined by KPI 1 and L the load applied in a time step. The tangential stiffness is expected to be constant as long as predominantly linear behaviour is observed. Therefore it was expected that the change in behaviour could be detected faster by applying KPI 2 compared to KPI 1. With a so called windowed approach the gradient could be computed real-time during a test. In Fig. 5 the tangential stiffness is plotted against time. Detailed analysis made clear that peaks occur in periods of constant load where dL is very small and small changes in dκ may have no physical meaning, therefore it was concluded that KPI's based on parameters with dL should be treated with care.

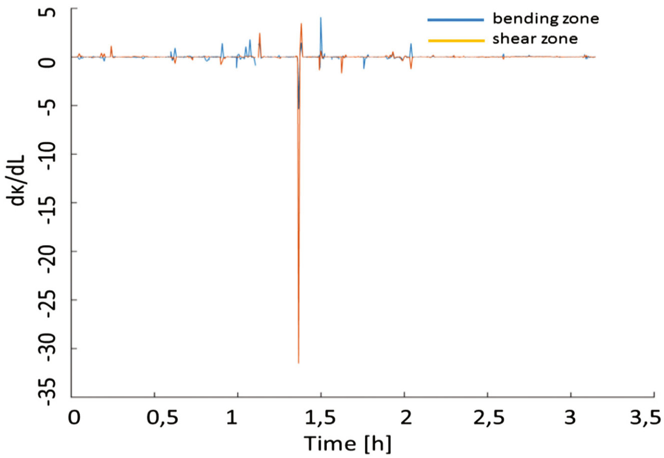

Fig. 5. Tangential stiffness development in time in test B10E1.

8 KPI 3 Tension Stiffening

Another parameter that represents a change in physical behaviour is the tensile deformation of the specimen at the level of reinforcement. Such behaviour is usually related to the tension stiffening effect. The occurring of cracks in the tension zone causes a change in stiffness in this area. Because the compressive deformation of a cross section is usually limited compared to the tensile behaviour, KPI 3 turns out to be comparable to KPI 1.

9 KPI 4 Diagonal Deformation

A parameter that is difficult to measure on site is the strut deformation (inclined LVDT's in Fig. 1). The strut deformation analysis is performed because these measurements may provide early indications of a shift of failure mode from the bending (theoretically expected according to perfect beam theory) towards a shear failure mode. Results of the analysis did not lead to satisfactory outcome.

10 KPI 5 Bending – Shear Curvature Ratio

Based on analysis of KPI 1 – KPI 4, it was concluded that the ratio of the curvature or tension stiffening in the bending and shear zones should be studied. To set a objective evaluation criterion, a ratio of κ_b (bending) vs κ_s (shear) was determined under theoretical assumption of a linear behaviour of the member. In the presented test B10E1, the expected curvature ratio equals to $\kappa_b/\kappa_s = 2$. Hence, as long as in the experiment the shear zone does not show significant damage, the curvature ratio stays above 2.

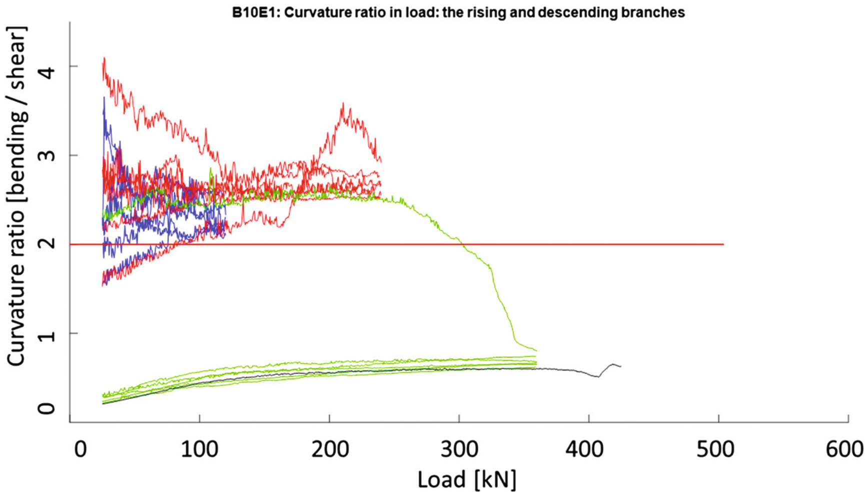

Fig. 6. Curvature ratio plotted against the applied load in test B10E1 (load stages are indicated in different colours: blue – 1st load level cycle, red – 2nd load level cycle, green – 3rd load level cycle).

In Fig. 4, it shows that the point of intersection of the KPI 5 line and limit line (KPI 5 = 2) is close to the point identified as Load = 340 kN; t = 1,3 h in the test.

When the curvature ratio is plotted against the applied load, a distinctive peak is visible at a load of 220 kN during the 2nd load level cycle long before failure at Load = 400 kN; t = 2,28 h (see red line Fig. 6). Note that for KPI 1 - KPI 4 the distinctive change was at t = 1,3 h (3th load level cycle), which was not early enough to avoid significant damage to the structure, as can be seen from the crack patterns of BEAM B10E1 in Fig. 7. The presented crack patterns were registered during the tests at the end of each load level cycle (after applying the load 3 times). In the crack pattern end of load level cycle 2, just after t = 1,2 h, only some bending cracks but no clear shear crack are observed. On the contrary, the crack pattern for load level 3, shows a clear shear crack which should be avoided in a load test on site.

11 KPI 6 Bending - Shear Tension Stiffening Ratio

The comparison between KPI 1 and KPI 3 showed that the tension stiffening effect (TS) is comparable to the curvature but is easier to measure during the testing. It was decided to focus on further evaluation of KPI based on the tension stiffening ratio, a ratio of $\varepsilon_{tension}$ (bending) vs $\varepsilon_{compression}$ (shear), since then only sensors at the tension side (in general the bottom) of the bridge are needed.

Since most of the damage is expected to occur as the load is raised for the first time, in Fig. 8 the tension stiffening ratio for load increase parts is shown. As can be seen, there tends to be a clear peak before the sharp drop of KPI 6 and intersection with the red line indicating theoretical level of TS_b/TS_s = 2. The clear peak is caused by the

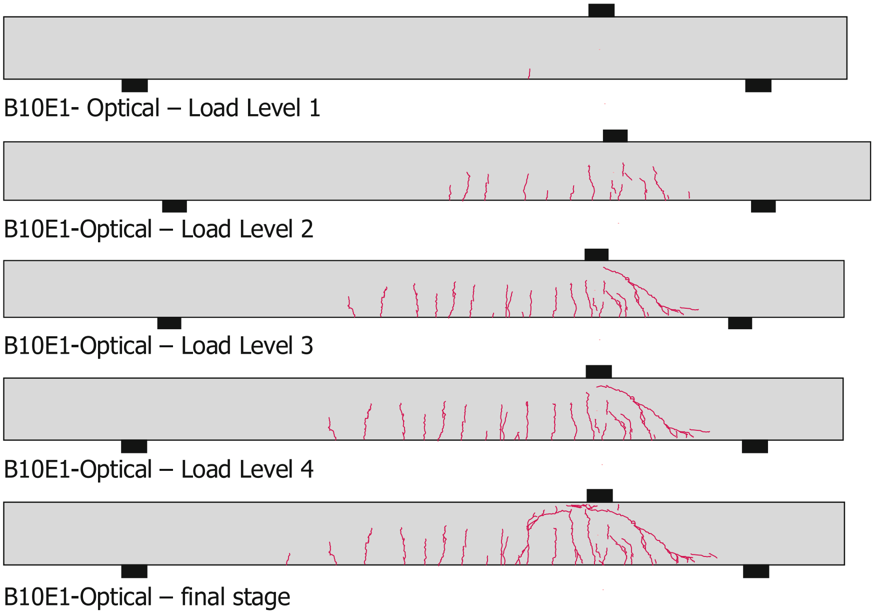

Fig. 7. Crack development in test B10E1 (Uijl den).

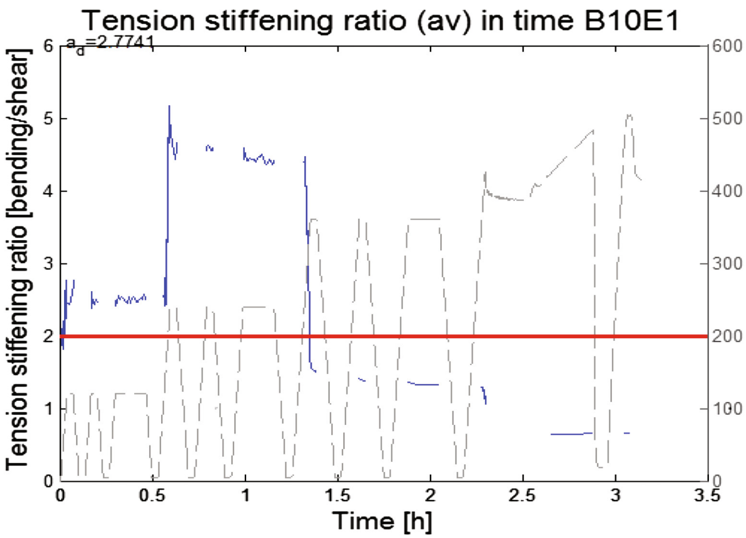

Fig. 8. Tension stiffening for the filtered load data in test B10E1.

reduction of the stiffness in the bending area, resulting in a load redistribution leading to higher loading of the shear area and reducing the stiffens there as well. Since the stiffness reduction in the bending area is higher, the ratio stays above the theoretical

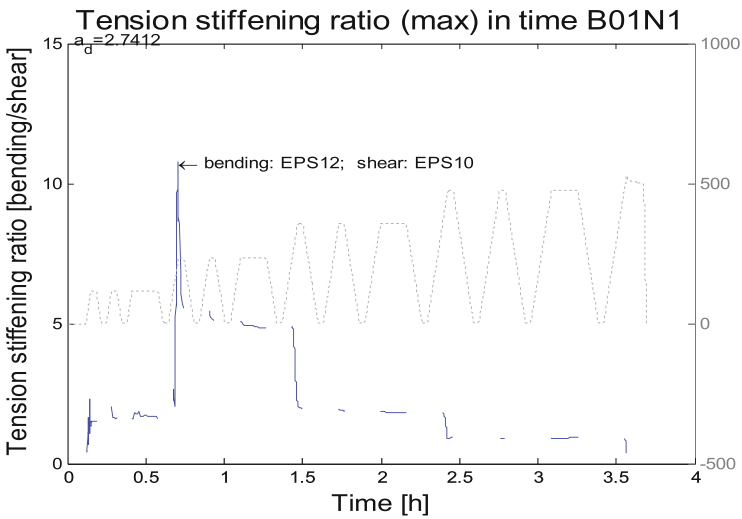

Fig. 9. Tension stiffening for the filtered load data of B01N1.

ratio of 2. As can be seen in Fig. 8, the KPI tends to stay constant under an equal load. With further increase of the load (load level 3) and further grow of the damage, an apparently stronger weakening of the shear region takes place, which is manifested by drop of the KPI below 2. Question was whether this behaviour would be observed in other tests as well. Therefore more tests were analysed (see example in Fig. 9) showing comparable results and further analysis are ongoing at the moment.

12 Conclusions

Results of several laboratory tests on full-scale shear beams have been examined, confirming that a change in structural behaviour at an early stage during testing can be traced by the proposed indicator, based on measurements performed only on the tensile side of the tested specimen, which is of importance for its applications to existing structures, with limited access for measurements. The measurements where applied at the level of the reinforcement, the effect of measurement on the bottom or top surface of the structure should be studied since in load tests this would be the preferred case. An algorithm for data analysis has been developed, which can be used to control the proposed performance indicator in real time during testing.

Acknowledgement. The beam tests used for the work reported were sponsored by the Dutch Ministry of Infrastructure and the Environment. The authors are grateful to the sponsor for this. The views expressed here are those of the authors and not necessarily those of the Ministry.

References

ACI (American Concrete Institute): Code Requirements for Load Testing of Existing Concrete Structures, ACI 437.2-13, Farmington Hills, USA, January 2014

DAfStb-Richtlinie: Belastungsversuche an Betonbauwerken, Deutscher Ausschuß für Stahlbeton –DafStb Berlin, Berlin, September 2000

Uijl den, J., Yang, Y.: Comparative study of shear capacity on beams of 50-years old and new concrete, TU Delft Stevin Report 5.25-09-06 (2009)

Yang, Y., den Uijl, J., Dieteren, G., de Boer, A.: Shear capacity of 50 years old reinforced concrete bridge without shear reinforcement. In: The 3rd Congress of the International Federation for Structural Concrete, Washington DC (2010)

Yang, Y.: Shear behaviour of reinforced concrete members without shear reinforcement, Thesis TU Delft, June 2014