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DEFINING LOADING CRITERIA FOR PROOF LOADING OF EXISTING REINFORCED CONCRETE BRIDGES

Rutger Koekkoek[1], Eva Lantsoght[1,2], Yuguang Yang[1], Ane de Boer[3] and Dick Hordijk[1]

[1]Department of Civil Engineering, Section Concrete Structures, Delft University of Technology, Delft, the Netherlands

[2]Politécnico, Universidad San Francisco de Quito, Quito, Ecuador

[3]Rijkswaterstaat, Ministry of Infrastructure and the Environment, Utrecht, the Netherlands

ABSTRACT

As the bridge stock in The Netherlands and Europe is ageing, various methods to analyse existing bridges are being studied. Proof loading of bridges is an option to study the capacity when crucial information about the structure is lacking. This information could be related to the material (for example, the effect of alkali-silica reaction on the structural capacity) as well as to the structural system (for example, the effect of restraints at the supports or transverse redistribution capacity). When it is decided to proof load a bridge, the question arises which maximum load should be attained during the experiment to approve the capacity of the bridge, and which criteria, based on the measurements during the test, would indicate that the proof loading needs to be aborted before reaching the maximum desired load (the so-called stop criteria). To define the required loading criteria, a review of the literature has been made, finite element models of existing viaducts have been made, and on these viaducts, proof loading tests have been carried out. These bridges were heavily instrumented, with a goal of learning as much as possible about the structural behaviour during proof loading. As a result of the analysis and experiments, recommendations are given for proof loading of bridges with respect to the required maximum load and the stop criteria. These recommendations are important, since they form the basis of a guideline for proof loading of existing concrete bridges that is under development in The Netherlands.

Keywords: assessment, concrete, proof loading, viaduct.

1. Introduction

Because of increasing national welfare and a growing population a lot of construction work was performed in the second half of the 20th century. For these historical reasons the Netherlands has built numerous roads and viaducts in the 60's and 70's. Sixty percent of the viaducts in the main road infrastructure were built before 1975 (Rijkswaterstaat 2007). Many of these viaducts are constructed using reinforced concrete and are located in highways and local roads. Since most of these viaducts were designed for a lifespan of 60 to 80 years (Rijkswaterstaat 2007), using the then prevailing design codes, they require an assessment of their condition according to the current loading levels and design codes.

For highways, intensive research to get insight in the condition of the reinforced concrete viaducts and bridges is already performed by Rijkswaterstaat (the Dutch Ministry of Infrastructure and the Environment). What is less known, is the condition of the bridges and viaducts in the local and regional roads. Although these viaducts are less frequently and less intensively loaded, their number is large. The maintenance of these local viaducts is under supervision of multiple organisations including Rijkswaterstaat, provinces, municipalities and water management institutes, which causes that the current structural condition of the older concrete viaducts is unknown for the majority of these objects.

Even when details, such as drawings, calculations, and design conditions for the assessment of a structure are present, it is not always clear how to determine the structural capacity and whether this capacity fulfils the prevailing code requirements. When a structure has physically degraded (e.g. Alkali Silica Reaction), it is even more difficult to assess the structure's capacity, since it is often not known how the degradation affects the structure. For these cases, and for cases in which additional load-bearing mechanisms can be activated that are not included in the calculations (Walraven 2010), load testing can act as a suitable method to determine the current capacity and performance of a structure. An example of a "hidden" load-carrying mechanism is the transverse redistribution capacity of slabs (Lantsoght et al. (in press)).

In general, two types of load tests can be distinguished. Proof load tests are load tests used to prove the structural capacity is larger than the design capacity of a structure. The second type of tests are supplementary or diagnostic load tests, which are loading a structure below the maximum expected live load during normal usage, and are intended to be used as an addition to theoretical calculations. In this paper the focus is on the first type of load tests: proof loading.

The aim of proof loading is to prove sufficient structural capacity for a structure by performing a relatively simple test in a short time span, requiring little preparations. Therefore, only a single tandem system will be applied to load the structure. During the proof loading, a limited number of measurements will be performed to check the structural behaviour by using predefined stop criteria. These criteria are load and deformation related limits, such as crack opening and load-deflection ratio's, which should not be violated during a test. Besides the stop criteria, Acoustic Emissions are measured to indicate possible damaging of the structure. When the loading test shows that the viaduct fulfils the requirements regarding the evaluated safety level, it is possible to update the structural capacity and as a result approve the viaduct for a longer life span.

2. Current state of proof loading research

Using proof loading to assess the capacity of a structure is not a new technique. This method was already used before on both civil works and buildings. Therefore, several documents regarding the assessment of existing structures have been developed by different organizations.

In Ireland, the document "Load Testing for Bridge Assessment" (National Roads Authority 2014) and in Great Britain, the "Guidelines for The Supplementary Load Testing of Bridges" (ICE 1998) cover the assessment of existing concrete or steel bridges. These documents mainly consider load tests as an addition to analytical assessments. Load tests are performed when it is suspected that additional capacity is present in a structure which cannot be identified using calculations. It is not allowed to use load testing as a self-supporting alternative to theoretical assessments.

The American Manual for Bridge Rating Through Load Testing (National Cooperative Highway Research Program and A.G. Lichtenstein and Associates Inc 1998) presents recommended load test procedures on existing bridges and provides a clear understanding in the usability of load tests and which measurements can be performed. Interesting examples are presented, however stop criteria are not provided.

In France, a method is described for newly built bridges and viaducts to verify the capacity before opening (Cochet et al. 2004). Measurements and inspection results are used to identify if defects are present in the structure. If no defects are found, the structure is allowed to open for public.

The aforementioned three documents do not provide a clear description of the test method or the method is not specially designed for civil works. On the other hand, there are three documents which cover the test loading process in more detail. These are discussed in the following sections.

2.1 German committee for reinforced concrete (Deutscher Ausschuss für Stahlbeton 2000) (DAfStb)

The German guideline, published by DAfStb (Deutscher Ausschuss für Stahlbeton 2000), describes a procedure for testing concrete structures using proof loading. The guideline is only valid for the proof loading of cast in-situ structures in plain or reinforced concrete. This document focusses on damaged or reused structures for which the calculation model, interaction of structural components or their parts, or the effectiveness of executed strengthening measures, is mathematically not sufficiently demonstrated.

The DAfStb Guideline prescribes that the load should be applied in at least three steps. After each step, at least one unloading step should be performed. The last load step should be an adequate sustained load.

In the DAfStb Guideline, stop criteria based on the deformation of the structure are presented. These criteria are the maximum allowable reinforcement and concrete strain, the allowable crack opening of new and existing cracks, and the maximum allowable permanent deformations.

2.2 *ACI 437.2M-13 (ACI Committee 437 2014)*

ACI code 437.2M-13 (ACI Committee 437 2014) provides requirements of performing a load test on a concrete structure, in addition to chapter 27 of ACI 318-14 (ACI Committee 318 2014). According to ACI code 437.2M-13, a load test may be conducted as part of a structural evaluation to determine whether an existing building requires repair or rehabilitation, or to verify the adequacy of repair and rehabilitations.

ACI 437.2M-13 presents monotonic and cyclic load test protocols, of which the cyclic loading protocol is of most interest for this paper. During a cyclic load test, at least three load levels should be applied, and each load level should have 2 cycles. The required load levels, step sizes and minimum load levels are indicated, see Fig. 1.

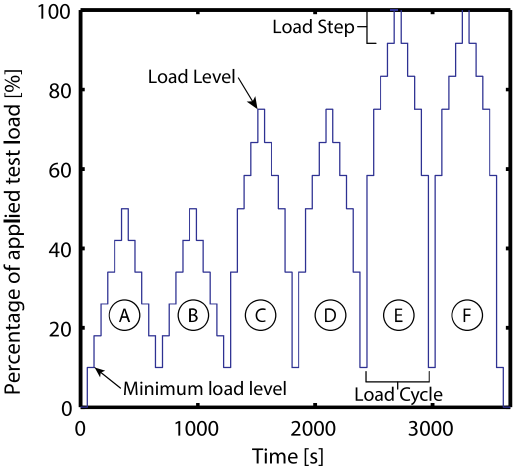


Fig. 1. Load levels and load steps as described by ACI 437.2M-13

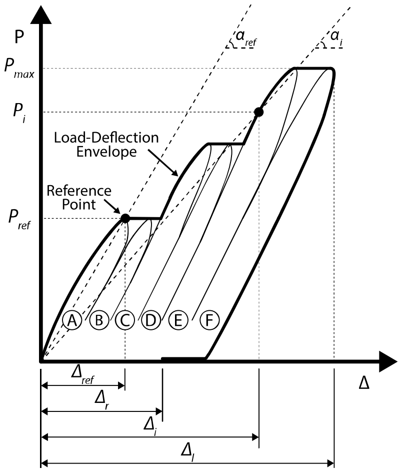


Fig. 2. Determination of ACI deviation from linearity index

After a load step, the deflection should be stable: the measured deflection variation over a period of at least 2 minutes does not exceed 10% of the initially measured deflection. Additionally, three other acceptance criteria are given: the deviation from linearity index, permanency ratio and residual deflection. The deviation from linearity index, see Fig. 2, is the most interesting criterion out of three. This criterion considers the non-linear behaviour of the tested structure by comparing the initial slope (α_{ref}) of the secant line of the load-deflection envelope at a reference point with the secant stiffness of a point at the load-deflection envelope during loading (α_i). For increasing load levels and cycling of loads, (permanent) deformations will increase and result in a decrease of the secant stiffness of the evaluated point on the load-deflection envelope. The allowable reduction in slope is limited to 25%.

3. Research at Delft University of Technology (DUT)

The documents presented in chapter 2 are related to load tests for the bending moment limit state, and not to limit states such as shear. Because allowable deformations for the shear limit state are different from those for bending moment, and sometimes even not measurable, the stop criteria presented are not usable for tests on shear. Therefore, DUT has been involved in proof loading tests in the Netherlands, where there is a large uncertainty regarding the structural safety of existing reinforced concrete slab bridges (Lantsoght et al. 2013b) as this type of bridge does not have shear reinforcement. Due to higher traffic loads and heavier live load models prescribed in NEN-EN 1991-2:2003 (CEN 2003) and new lower prescribed shear capacities in NEN-EN 1992-1-1:2005 (CEN 2005), the shear capacity for these viaducts is suspected to be not sufficient. In this section several applications related to proof loadings of concrete slab bridges are reviewed.

Both the proof loading method and the magnitude of the applied load have evolved. Initially, DUT was only involved in evaluating proof loadings performed in Heijdijk (Dieteren and Den Uijl 2009) and Medemblik (Kapphahn 2009). In 2007, the proof loading in Heijdijk was performed using a simple balanced loading frame and hydraulic jacks, and the viaduct was and loaded up to 640 kN. In later proof load tests, the German load vehicle BELFA (BELastungsFAhrzeug) was used which loaded a small bridge in Medemblik up to 545 kN. The proof loading of Vlijmen-Oost (Kapphahn 2013, Fennis et al. 2014, Koekkoek et al. 2015b), also using the BELFA, had a maximum load of 900 kN and was the first test where DUT performed measurements in addition to the Institute for Experimental Mechanics from Leipzig University of Applied Sciences (IFEM).

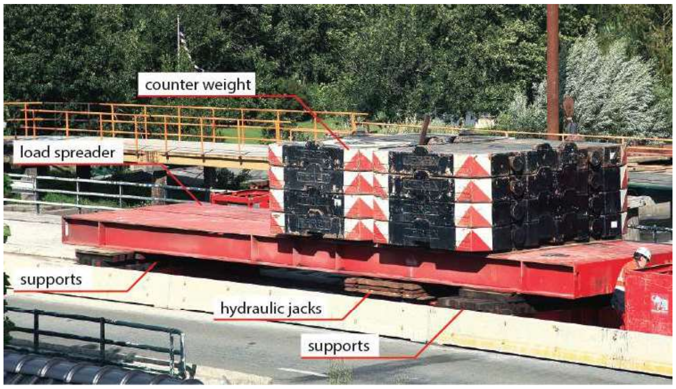


Fig. 3. Photograph of proof loading configuration as used by DUT

The first proof loading fully organized by DUT, using a load spreader and hydraulic jacks (Fig. 3), was applied to study the Halvemaans Bridge (Fennis and Hordijk 2014) which was loaded up to 900 kN. Next, the Ruytenschildt bridge (Lantsoght 2015) (Lantsoght et al. 2016) was tested. This experiment was special, since the bridge was loaded up to failure by applying a maximum load of about 4000 kN. In 2015 two more viaducts were tested: viaduct Zijlweg (Koekkoek et al. 2015a), which was loaded up to 1350 kN and viaduct De Beek (Koekkoek et al. 2016), loaded up to 1750 kN. During these proof loads no significant permanent damage developed.

The experiments mentioned above approved the capacity of the correspondent structures. In addition to that, they accumulate experiences and knowledge regarding proof loading of existing concrete slab bridges, based on which, a guideline for proof loading of existing concrete bridges can be developed.

4. Preparations for pilot proof loadings as performed by Delft University of Technology (DUT)

During the executed tests explained above, a general methodology on the preparation of proof loading has been developed at DUT. In this section it is discussed briefly. It mainly takes into account the dimension of the structure, the target limit state and eventually the magnitude of the applied load based on Eurocode Load Model 1 (EC LM1) from NEN-EN 1991-2:2003 (CEN 2003). The limit state for which the test is designated, needs to be determined. For the proof load tests performed by DUT, often the bending moment and shear capacity are of interest.

4.1 Determination of the viaduct dimensions

To calculate the required proof load, the dimensions of the viaduct should be known. It includes the physical dimensions of the viaduct such as span length, width and deck thickness and the layout in terms of number of lanes, sidewalks and parapets. The dimensions can be determined from original drawings when available. A visual inspection of the viaduct layout should take place to verify the possible deviations from the original layout.

4.2 Eurocode Load Model 1 (EC LM1) and the application in the Netherlands

EC LM1, as used for all levels of assessment (Lantsoght et al. 2013a, Vergoossen et al. 2013) in the Netherlands, is used to determine the proof load. The EC LM1 consists of two main loading components: a design tandem and a distributed lane load. The width of the carriageway determines the number of Notional Lanes (NL). Physical barriers can reduce the carriage width. Each NL is 3 m wide and is subjected to a design tandem and the distributed lane load, see Fig. 4. The area not defined as a NL is the remaining area (RA). Because applying multiple axle and a distributed load is not convenient in practice only a single tandem system consisting of two axle loads are applied during a proof loading.

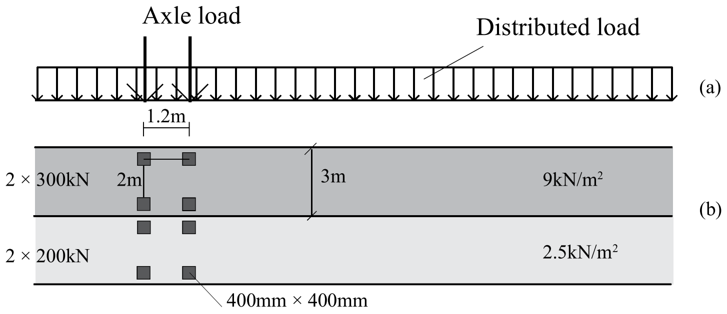


Fig. 4. Load Model 1 from NEN-EN 1991-2:2003. (a) Side view; (b) Top view

In the Netherlands the EC LM1 is used in conjunction with the guideline for existing structures “RBK” (Rijkswaterstaat 2013), and NEN 8700:2011 (Code Committee 351001 2011). The RBK presents four safety levels, corresponding to different reliability indices β and reference periods, as listed in Table 1. Viaducts in the Netherlands have to fulfil at least the requirements of the RBK Usage level, corresponding with a remaining life span of 30 years. When possible, the safety level Newly Built should be proven. For the permanent self-weight, which is only the main structure, a lower safety factor of 1.10 is used, see Table 1. This factor takes the uncertainties in the structural dimension into account. Because these dimensions are determined during the preparations of the proof loadings, and are unlikely to change in the future, the factor could be reduced.

Table 1. Reliability index, reference periods and safety factors presented in RBK (Rijkswaterstaat 2013)

Safety level	**β factor**	**Reference period**	**Remaining life span**		**γ permanent self-weight**	**γ quasi-permanent self-weight**	**γ variable load**
Newly built	4.3	100 year	100 year		1.10	1.25	1.50
Reconstruction	3.6	30 year	30 year		1.10	1.15	1.30
Usage	3.3	30 year	30 year		1.10	1.15	1.25
Disapproval	3.1	15 year	1 year		1.10	1.10	1.25

4.3 Location of the proof load

The location of the proof load is in general the most unfavourable position for the considered limit state. However, when the critical span of a viaduct crosses a road or a highway, loading above this road when traffic is passing underneath will not be allowed. In that case, either the road underneath should be closed or a different span of the structure should be chosen and the results should be extrapolated.

For the limit state of bending, the proof load should be placed at the location which results in the highest bending moment. The critical loading position can be determined with FEM models. The size of the wheel prints should be corrected by incorporating the load distribution through the asphalt layer and half of the height of the concrete deck and the mesh size. Using the FEM models, the maximum moment location is found by shifting the proof loads across the longitudinal axis of the structure, see Fig. 5. When the axis of the viaduct is skewed with respect to the axis of the driving lane, the mutual distance for proof loads in adjacent lanes should be varied. After studying all these positions, the location causing the highest bending moment is chosen as the proof loading location.

For the limit state of shear, only the slab thickness and the reinforcement configuration at the location which should be tested, are taken into account. Since the highest shear forces occur near the supports, the thickness close to the supports is governing. Research (Lantsoght et al. 2013b, Lantsoght et al. 2014b) showed that the governing distance between the face of the first axle and the face of the support equals 2.5*d*.

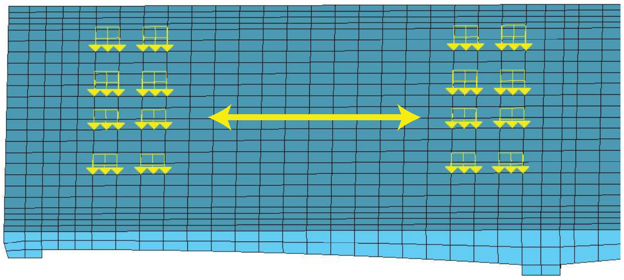


Fig. 5. Shifting of wheel prints along the longitudinal axis in FEM model

4.4 Magnitude of proof load

For practical reasons, as mentioned before, only a single tandem system consisting of four concentrated loads representing the wheel prints is applied during a proof loading. Therefore, the load on these wheel prints should be increased to incorporate the effect on the evaluated cross-section of the distributed lane load and eventual loads in other notional lanes. As a result the bending moment acting in the evaluated cross section should be equal for both the EC LM1 and the applied proof load.

The single tandem system is placed at the location that causes the highest bending moments according to EC LM1. Hereby it is assumed that the location where the maximum bending moment occurs is the same for the EC LM1 model and the single tandem system. By evaluating the load only in one cross section it is also assumed that the ratio between the proofed capacity and the design capacity is equal for the entire structure.

4.4.1 Magnitude of proof load for multiple notional lanes

When a structure is assessed for more than one notional lane using EC LM1, FEM model calculations are showing that the highest bending moment is found in notional lane 1, caused by the larger axle loads (see Fig. 4). For the proof loading of viaduct Vlijmen-Oost, the contribution of all loaded lanes on the maximum moment found in notional lane 1 is determined. The loads in lane 1 are contributing to 59% of the maximum moment. For lane 2 this contribution is 14% and for lane 3 only 3% (Koekkoek et al. 2015b). The influence of adjacent lanes on the maximum moment is thus limited compared with the load applied in lane 1. To incorporate the influence of the adjacent lanes into the concentrated loads applied in lane 1, the loads on the wheel prints (600 kN) should be increased with 100% to 180% depending on the evaluated safety level.

The data presented above are based on the evaluation of the maximum bending moment at a specific point in the structure. In reality, this high peak load is distributed over the width of the structure. Because of redistribution of bending moments due to cracking of the structure, DUT averages the bending moment over a width of 3 m. As a result, the absolute moments become smaller, but the required proof load will not change significantly: only 2% (Koekkoek et al. 2015b). When the values are averaged over a larger width, the difference becomes larger: up to 7% when averaging over 5 m width (Koekkoek et al. 2016).

For the determination of the proof load for the limit state of shear, a set load distribution is provided. Research showed that the shear forces should be averaged over a width of 4d (Lantsoght et al. 2013a, Lantsoght et al. 2014a).

5. Execution of proof loading

To apply the proof load in a safe way, a load spreader and hydraulic jacks are used, see Fig. 3. which has the advantage of transferring back the applied load to the supports when the structure undergoes excessive deflections. The proof load itself is applied according to a loading scheme with predefined load levels, representing various safety levels and critical load stages, and are used in combination with measurements to check the stop criteria and judge whether it is safe to continue the test to a higher load level.

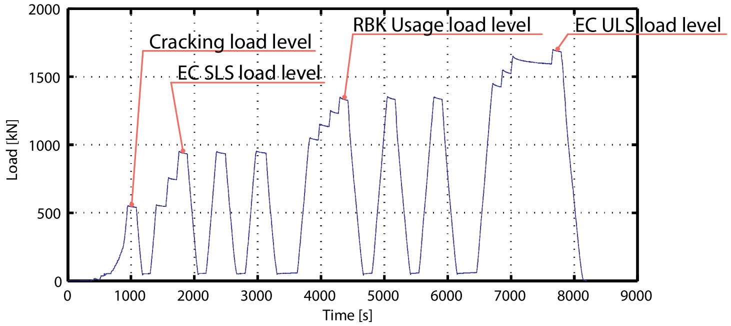


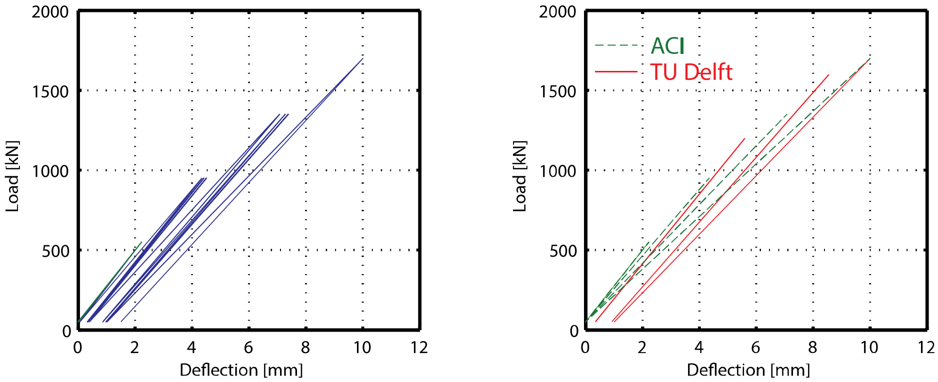
Fig. 6. Example of loading scheme for applied proof load

5.1 Loading scheme

The loading scheme followed by DUT, see Fig. 6, is comparable to the DAfStb (Deutscher Ausschuss für Stahlbeton 2000) and ACI 437.2M-13 (ACI Committee 437 2014) guidelines. The various load levels, are applied using load increments and by performing three load cycles per load level. These cycles investigate the added deformation during the first load cycle and whether the deformations are increasing when applying the same load multiple times. Cycles are also necessary for Acoustic Emission measurements. The loads are released to investigate the residual deformations. The last load level, which represents the highest safety level, is applied for a longer period to investigate the long term behaviour of the structure. Equal speeds during loading and unloading during the test is aimed for to compare the measurements results under the same loading conditions.

5.2 Stop Criteria

Stop criteria use measurements to verify the non-linear response of the structure and are used to avoid permanent damage to the structure. The most important measurements are the load, the vertical deformation of the deck measured at several locations, the average strain at the concrete surface at several locations, the opening of existing cracks and Acoustic Emissions. An important aspect for the evaluation of stop criteria are the permanent deformations.



(a) (b)

Fig. 7. Load deflection curve (a) and slopes (b) according to ACI and TU Delft method

5.2.1 Relationship between applied load and deformations

At the first load cycles, the load level is usually low, therefore the structure behaves linearly. In these cycles, the stiffness of the structure with the applied load condition is determined. For further load steps the slope of the loading curve is compared with the initial load-deformation slope. When the difference between these slopes is more than 25%, the loading should be aborted. This criterion is slightly differing from the ACI Deviation from linearity index where slopes are measured from the origin, which may cause that for larger permanent deformations the 25% limit can be violated even when the slope of the loading branches is still equal. This difference is indicated in Fig. 7 where the ACI deviation from linearity index and the method used by DUT are presented. From Fig. 7 (b) it can be seen that the reduction in slope for the ACI method is larger (-27%) than for DUT method (-19%). Besides the load-deflection relation, the relation between the applied load and the measured strain is regarded as a stop criterion. The load-strain relations are evaluated at the same way as the vertical deformations. Formulation of this stop criterion is still in development to create a solid criterion useful during proof loadings for the limit states flexure and shear.

5.2.2 Relationship between maximum and residual deformations or crack openings

During proof loading the restrictions to residual deformations and crack openings as presented in the DAfStb are used. This holds that the residual deformation after a load cycle shall be lower than 10% of the maximum deformation measured for the evaluated load cycle, and that residual crack opening of existing cracks should be limited to 20% of the maximum measured crack width. During a load test no one is allowed to be close to the tested span. Therefore criteria for newly formed cracks are not practically usable.

5.3 Usability of stop criteria

Up to now, the test loads performed by DUT were not aborted due to violations of stop criteria. A reason for this is that the definition of solid stop criteria has not completed, and thus stop criteria are not used as a stand-alone methodology yet but only as an additional warning. Despite this, the functionality of stop criteria is increasing after each successive load test. The proof loading of the Ruytenschildt bridge (Lantsoght 2015) up to failure also provides valuable information on the upper limit of allowable deformations, which is used to validate the functionality of the stop criteria. Research on the stop criteria (Tersteeg 2015) on performed load tests and tested beams in the Stevin II Laboratory showed that there is a large variation in performance of stop criteria when used on structures without a loading history, or already loaded to a large extent. For lower load levels, the stop criteria are sometimes showing false positives, caused by the relative large permanent deformations during small loadings. When sudden failure can be expected without showing excessive deformation, for example for shear failure, the currently available stop criteria will not warn in time. Therefore, AE measurement results are consulted. AE measurements are showing high activity when a structure is close to failure. The load level at which a stop criterion is activated as well as the difference between failure modes should be accounted for in the further definition of stop criteria.

6. Future research

DUT aims at developing a guideline for the proof loading of existing concrete bridges. As part of this guideline, the relation between the applied load and the condition of the structure should be further investigated. The loading methodology will be developed and defined further. Clear and realistic stop criteria used during proof loads should be further developed for both the limit states of bending and shear. For the latter, using Acoustic Emission measurements can be suitable. Accurate and simple measurements should be defined which are the input for the stop criteria. These elements aim at obtaining the required information about the condition of a structure with the smallest possible effort.

7. Summary and conclusions

Because a large part of the viaduct stock in The Netherlands was built in the 60’s and 70’s and these structures are approaching the end of their designed life span, they require an assessment according to current requirements. Since it is not always possible to do this in an analytical way, proof loading of existing concrete viaducts is suggested to prove sufficient structural capacity and extend the life span.

Load testing has been discussed in multiple documents and guides, but only few of them are providing usable load- and stop criteria for proof loading of concrete viaducts. Therefore, Delft University of Technology (DUT) performed three proof loads; in the first place to prove the structural capacity of the structure, but also to gain experience with, and elaborate a guideline on proof loading.

The preparations for proof loading at DUT consist of mainly four components: determining the viaduct dimensions, determining the load configuration according to Eurocode Load Model 1, determining the location of the proof load using FEM models and at last determining the proof load magnitude for various safety levels using the gathered information. During a proof loading DUT tests on two limit states: bending and shear, each having specific requirements regarding location and load spreading.

The proof load is applied following a predefined load scheme, which increases the load stepwise and cycles the load in order to check the structural behaviour by consulting the measurements performed on the viaduct. Stop criteria are used to judge whether it is safe to proceed the proof loading to a higher load level. These criteria are based on (permanent-) deformation and crack opening measurements. When sudden failure is expected, e.g. in case of shear failure, Acoustic Emission measurements are consulted.

Although the used criteria are not yet a dedicated method for judging the structural behaviour, all performed proof loadings are contributing to establish solid stop criteria which will be part of a guideline on proof loading on existing concrete bridges, as will be elaborated at DUT.

8. Acknowledgements

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References

ACI Committee 318 2014. *Building Code Requirements for Structural Concrete and Commentary,* Farmington Hills, MI, USA, American Concrete Institute.

ACI Committee 437 2014. *Code Requirements for Load Testing of Existing Concrete Structures (ACI 437.2M-13) and Commentary,* Farmington Hills, MI, USA, American Concrete Institute.

CEN 2003. Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges, NEN-EN 1991-2:2003. Brussels, Belgium: Comité Européen de Normalisation.

CEN 2005. Eurocode 2: Design of Concrete Structures - Part 1-1 General Rules and Rules for Buildings. NEN-EN 1992-1-1:2005. Brussels, Belgium: Comité Européen de Normalisation.

Cochet, D., Corfdir, P., Delfosse, G. & Jaffre, Y. 2004. *Load tests on bridges and pedestrian bridges: technical guide (in French),* Bagneux Cedex, France, Sétra.

Code Committee 351001 2011. *Assessement of structural safety of an existing structure at repair or unfit for use - Basic Requirements, NEN 8700:2011 (in Dutch),* Delft, The Netherlands, Civil center for the execution of research and standard, Dutch Normalisation Institute.

Deutscher Ausschuss Für Stahlbeton 2000. DAfStb-Guideline: Load tests on concrete structures (in German). Berlin, Germany: Deutscher Ausschuss fur Stahlbeton,.

Dieteren, G. G. A. & Den Uijl, J. A. 2009. Evaluation proof loading Heijdijk (in Dutch). Delft, The Netherlands.

Fennis, S. A. A. M. & Hordijk, D. A. 2014. Proof loading Halvemaans bridge Alkmaar (in Dutch). Stevin Report 25.5-14-05. Delft, The Netherlands: Delft University of Technology.

Fennis, S. A. A. M., Van Hemert, P. H. A., Hordijk, D. A. & De Boer, A. 2014. Proof loading viaduct Vlijmen-Oost (in Dutch). *Cement,* 5**,** 40-45.

Institution of Civil Engineers & National Steering Committee for the Load Testing of Bridges 1998. *Guidelines for the Supplementary Load Testing of Bridges,* London, United Kingdom.

Kapphahn, G. 2009. Experimental structural safety review of the superstructure of bridge No.12 (14H04) in the road N240 near Medemblik (in German). Markkleeberg, Germany.

Kapphahn, G. 2013. Viaduct Vlijmen-Oost (NL), loat test with the BELFA (in German). Markkleeberg, Germany: ifem.

Koekkoek, R. T., Lantsoght, E. O. L. & Hordijk, D. A. 2015a. Proof loading of the ASR-affected viaduct Zijlweg in highway A59. Stevin Report 25.5-15-08. Delft, The Netherlands: Delft University of Technology.

Koekkoek, R. T., Yang, Y., Fennis, S. A. A. M. & Hordijk, D. A. 2015b. Assessment of Viaduct Vlijmen Oost by Proof Loading. Stevin Report 25.5-15-10. Delft, The Netherlands: Delft University of Technology.

Koekkoek, R. T., Yang, Y. & Hordijk, D. A. 2016. Analysis report for the assessment of Viaduct De Beek by Proof Loading. Stevin Report 25.5-16-01. Delft, The Netherlands: Delft University of Technology.

Lantsoght, E. O. L. 2015. Ruytenschildtbrug: Analysis of test results ultimate limit state (in Dutch). Stevin Report 25.5-15-05. Delft, The Netherlands: Delft University of Technology.

Lantsoght, E. O. L., De Boer, A. & Van Der Veen, C. 2014a. Determination of distribution width for shear stresses at support in reinforced concrete slab bridges. *EuroC.* St. Anton am Arlberg, Austria.

Lantsoght, E. O. L., De Boer, A., Van Der Veen, C. & Walraven, J. C. 2013a. Peak shear stress distribution in finite element models of concrete slabs. *In:* ZINGONI, A. (ed.) *Research and Applications in Structural Engineering, Mechanics and Computation.* Cape Town, South Africa: Taylor and Francis.

Lantsoght, E. O. L., Van Der Veen, C. & De Boer, A. 2016. Shear and moment capacity of the Ruytenschildt bridge. *IABMAS 2016.*

Lantsoght, E. O. L., Van Der Veen, C., De Boer, A. & Walraven, J. (in press). Transverse Load Redistribution and Effective Shear Width in Reinforced Concrete Slabs. *Heron*, 29 pp. .

Lantsoght, E. O. L., Van Der Veen, C., De Boer, A. & Walraven, J. C. 2013b. Recommendations for the Shear Assessment of Reinforced Concrete Slab Bridges from Experiments *Structural Engineering International,* 23**,** 418-426.

Lantsoght, E. O. L., Van Der Veen, C., Walraven, J. & De Boer, A. 2014b. Recommendations for the Shear Assessment of Reinforced Concrete Solid Slab Bridges. *IABMAS 2014.* Shanghai, China.

National Cooperative Highway Research Program & A.G. Lichtenstein and Associates Inc 1998. *Manual for Bridge Rating Through Load Testing*, Transportation Research Board, National Research Council.

National Roads Authority 2014. Load Testing for Bridge Assessment. Dublin, Ireland.

Rijkswaterstaat 2007. Inventarisation civil works (in Dutch). Utrecht, The Netherlands: Rijkswaterstaat.

Rijkswaterstaat 2013. Guideline on assessing civil works: judging the structural safety of an existing civil work for renovation, usage and disapproval. (in Dutch). Utrecht, The Netherlands: Rijkswaterstaat.

Tersteeg, R. H. D. 2015. Proof loads on concrete bridges (in Dutch). Delft, The Netherlands.

Vergoossen, R., Naaktgeboren, M., 'T Hart, M., De Boer, A. & Van Vugt, E. 2013. Quick Scan on Shear in Existing Slab Type Viaducts. *International IABSE Conference, Assessment, Upgrading and Refurbishment of Infrastructures.* Rotterdam, The Netherlands.

Walraven, J. C. 2010. Residual shear bearing capacity of existing bridges. *fib Bulletin 57, Shear and punching shear in RC and FRC elements; Proceedings of a workshop held on 15-16 October 2010.* Salò, Lake Garda, Italy.