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Stop criteria for proof load testing using a traffic light system

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Abstract

During a proof load test on a bridge, high magnitude loads are applied. To avoid causing irreversible damage, thresholds to the structural responses, the so-called stop criteria, need to be defined. This paper proposes to categorize stop criteria into three levels: green light (related to the serviceability limit state), yellow light (related to potential irreversible damage) and red light (related to potential local collapse). For the Ultimate Limit State, stop criteria for shear and flexure are defined. Shear stop criteria are derived from mechanical models, using traditional strain measurements and acoustic emission measurements. These stop criteria are validated with experiments on reinforced concrete slab strips, straight slabs, and skewed slabs. The resulting traffic light system gives the bridge engineer a tool to make decisions during a proof load test. This approach is a step forward in the interpretation of structural responses during proof load testing.

Keywords: assessment; bridge testing; damage indicators; experiments; flexure; mechanical models; proof load testing; shear; stop criteria; traffic light system

1 Introduction

In many parts of the world, the existing bridge stock is aging, which increases the need for assessment [1-3]. In the Netherlands, for example, a large number of bridges date back to the 1960s and 1970s, the era of the expansion of the national road network. These bridges were designed for the live loads of that time period, which are lower than the currently used live loads, and using capacity models that differ from the models used in our current codes. As a result, upon an initial assessment, a large number of existing reinforced concrete solid slab bridges in the Netherlands are found to be shear-critical and require further analysis.

In the Netherlands, assessment of reinforced concrete solid slab bridges is carried out using Levels of Approximation for Assessment, also known as Levels of Assessment [4]. The first level uses hand calculations, the second level uses linear finite element models to better evaluate the load effect, and the third level uses either probabilistic models or nonlinear finite element models. Ultimately, the fourth and final level of assessment involves the use of proof load testing to directly demonstrate that a given bridge can carry the code-prescribed factored loads.

During a proof load test on a bridge, high magnitude loads are applied, as these loads are to be representative of the code-prescribed factored load combination. To avoid causing irreversible damage or even collapse of the bridge, it is important to define thresholds to the structural responses, the so-called stop criteria, before the test.

The requirements for the stop criteria are that they need to be measurable during the proof load test, that they need to be broadly applicable, and that they need to be safe enough on one hand to avoid irreversible damage to a bridge during proof load testing and that they cannot be overly conservative on the other hand, as such conservatism would lead to ending a proof load test prematurely and potentially without reaching the target load level.

This paper addresses the need for defining a complete set of stop criteria, that are easy to measure, broadly applicable, based on mechanical models, and that are validated with different series of experiments.

2 Proposed stop criteria

This paper proposes to categorize stop criteria into three levels:

- green light (related to the serviceability limit state),
- yellow light (intermediate state) and
- red light (related to potential local collapse).

For the Ultimate Limit State, which is linked to the yellow and red light, stop criteria for shear and flexure are defined. The stop criteria for shear are derived from mechanical models: the Critical Shear Displacement Theory [5] and the Critical Shear Crack Theory [6]. These theories are linked to measurable responses, and in particular traditional strain measurements. In addition, a set of stop criteria based on a different physical parameter, i.e. acoustic emission measurements, is developed to provide redundancy and increase the safety of the application.

Table 1 summarises the stop criteria, giving the objective of each criterion, the indicator applied, the physical meaning of the indicator, and the action the bridge engineering can take during the test based on the information of the stop criterion.

In Table 1, a number of parameters are used. The stop criterion for crack width for serviceability is expressed based on the average crack width w_{avg} and given as:

$$w_{avg} = \frac{\varepsilon_{c,average} l_g}{n_{cr}} \leq 0.3mm \tag{1}$$

The number of cracks n_{cr} represents the average number of cracks within the gauge length l_g. The difference between the crack spacing between major cracks and secondary cracks at the reinforcement level is considered using a factor of 0.5, resulting in:

$$n_{cr} = \frac{l_g}{0.5 l_{crm}} \tag{2}$$

with l_{crm} the average crack spacing.

The shear stop criteria are a function of the position of the measurement, which is expressed as a function of M/Vd with M the sectional moment, V the sectional shear, and d the effective depth to the longitudinal reinforcement. This value is normalized with $\lambda = a/d$ the shear span to depth ratio. Two indicators are used for shear: I_{CSDT} is based on the Critical Shear Displacement Theory:

$$I_{CSDT} \approx \frac{V(w-0.01)}{bd} = \tau(w-0.01) \tag{3}$$

which is a measurable parameter as a function of the shear stress τ and the crack width w. The critical shear indicator $I_{CSDT,cr}$ then becomes:

$$I_{CSDT,cr} = 0.03 f_c^{0.56} \frac{s_{cr}}{d}\left(-978\Delta_{cr}^2 + 85\Delta_{cr} - 0.27\right) \tag{4}$$

with f_c the cylinder concrete compressive strength, and the critical shear displacement:

$$\Delta_{cr} = \frac{25d}{30610\phi_{eq}} + 0.0022 \leq 0.025 \tag{5}$$

as a function of the equivalent reinforcement diameter φ_{eq}:

$$\phi_{eq} = \frac{\Sigma\phi_i^2}{\Sigma\phi_i} \tag{6}$$

Table 1. Overview of proposed stop criteria, indicating the traffic light system color

Objective	Indicator	Physical meaning	Action
Serviceability limit state	w_{avg}	Onset of cracking in reference region	Understand that section changes from uncracked to cracked
Serviceability limit state	AE-based green-light criterion	Wave-based signal of cracking detected	Understand that section changes from uncracked to cracked
Shear	min(I_{CSDT}, I_{CSCT}) in 0.8 < $M/Vd×(1/λ)$ < 1	Local reaching of lower bound of shear capacity from mechanical models	Intermediate warning level
Shear	min(I_{CSDT}, I_{CSCT}) near load for loads in middle of width and in 0.8 < $M/Vd×(1/λ)$ < 1 for loading near edge	Local reaching of lower bound of shear capacity from mechanical models	Intermediate warning level
Shear	Initiation of inclined cracks	Development of shear cracking	Intermediate warning level
Shear	AE-based yellow-light criterion	Cracking in the strut	Intermediate warning level
Shear	Damage ratio of 0.5	Half of the strut width deteriorated	Intermediate warning level
Shear	min(I_{CSDT}, I_{CSCT}) in < $M/Vd×(1/λ)$ < 0.7	Shear-carrying mechanisms nearly achieved in critical region	Further loading can result in (local) collapse
Shear	min(I_{CSDT}, I_{CSCT}) at 1.5d in the middle as well as at 2d in width direction from load for loads in middle of width and in $M/Vd×(1/λ)$ < 0.7 for loading near edge	Local reaching of aggregate interlock capacity	Further loading can result in (local) collapse
Shear	Further development of inclined cracks, typically monitored using DIC	Full shear cracking	Further loading can result in (local) collapse
Shear	Red-light AE criterion	Cracking in strut significantly reduces capacity	Further loading can result in (local) collapse
Shear	Damage ratio near 1	Almost entire strut width deteriorated	Further loading can result in (local) collapse
Flexure	Minimum of stop criteria for residual crack width, stiffness reduction, deflection profiles	Changes in flexural behavior and load distribution occurring	Intermediate warning level
Flexure	Minimum of stop criterion for limiting strain or limiting crack width based on yielding of steel	Local yielding of reinforcement steel	Further loading can result in (local) collapse

and s_{cr} the height of the fully developed crack as a function of the reinforcement ratio ρ and the modular ratio n:

$$s_{cr} = \left(1 + \rho n - \sqrt{\rho n + (\rho n)^2}\right) d \quad (7)$$

For use with slab members, the waviness of the crack profile needs to be considered. Until further research on this topic is available, this factor is taken into account by multiplying Δ_{cr} with a value of 1.27.

The stop criterion based on the Critical Shear Crack Theory is [7]:

$$I_{CSCT} = \tau\left(1 + 120\frac{w}{d_g}\right) \le \frac{\sqrt{f_c}}{3} \quad (8)$$

The measurable parameter is a function of the crack width and shear stress, which can be derived from the sectional shear, and the known value of the maximum aggregate size d_g. The threshold is related to the cylinder concrete compressive strength f_c.

The flexural stop criteria combine various indicators of global slab behaviour at the yellow light level, including qualitative indicators: changes in the load-deflection curve, changes in the transverse deflection profile, changes in the longitudinal deflection profile, and $w_{res} \leq 0.2w_{max}$ (with w_{res} the residual crack width after load removal and w_{max} the crack width at maximum loading) for members previously cracked in bending and $w_{res} \leq 0.3w_{max}$ for members not previously cracked in bending.

At the red light level, two flexural stop criteria are used. The strain limit is:

$$\varepsilon_c \leq \varepsilon_{c,bot,\max} - \varepsilon_{c0} = \varepsilon_{stop} \tag{9}$$

with

$$\varepsilon_{c,bot,\max} = \frac{h-c}{d-c} \times \frac{f_{ym}}{E_s} \tag{10}$$

where ε_{c0} is the analytically determined short-term strain in the concrete caused by the permanent loads acting on the structure before the application of the proof load, $\varepsilon_{c,bot,max}$ is the concrete strain at the bottom of cross-section that corresponds to a yield stress in the steel of the yield strength, c is the height of the compression zone, found using Thorenfeldt's parabola and sectional equilibrium, h is the height of cross-section, f_{ym} is the average yield strength of the tension reinforcement steel, and E_s is the modulus of elasticity of the reinforcing bars.

The crack width limit is:

$$w_{stop} = 2\frac{f_{ym} - f_{perm}}{E_s}\beta_{fr}\sqrt{d_c^2 + \left(\frac{s}{2}\right)^2} \tag{11}$$

where f_{perm} is the stress in the steel caused by the permanent loads, β_{fr} is the strain gradient factor used in the method of Frosch [8], d_c is the cover to the centroid of the tension reinforcement, and s is the reinforcement spacing.

Finally, the shear stop criteria are complimented with a set of stop criteria based on acoustic emission measurements, where the indicator is related to cracking reaching the compressive strut [9].

3 Experiments

3.1 Slab strips

The first series of experiments used to validate the developed stop criteria (with a focus on the shear stop criteria) consists of slab strips of 10 m length, 0.3 m width and heights of 500 mm, 800 mm and 1200 mm, which are tested in cycles of loading. The span length is 9 m. Concrete C65/80 is used and steel B500B is used for the reinforcement.

The following parameters are varied in this series of tests: height of the specimen, location of the load, and reinforcement ratio. In total, 14 experiments are used for the validation [7, 10, 11].

3.2 Straight slabs

A second series of experiments used for the validation of the developed shear stop criteria consists of straight slabs failing in shear and flexure, subjected to cycles of loading to mimic a proof load test, and heavily instrumented to study the development of strains and cracks [12]. The slabs are 5 m in length, with a span of 3.6 m, 2.5 m in width and 0.3 m thick. Concrete C35/45 is used and steel B500B is used for the ribbed reinforcement and plain bars with 304 MPa yield strength are used for the specimens reinforced with plain reinforcement bars.

From this series of experiments, five experiments are selected for the comparison to the stop criteria: experiments loaded in the middle of the width, and failing in shear. The following parameters are varied in this series of tests: testing near the simple of continuous support, using plain or ribbed reinforcement, reinforcement ratio, and distance between the load and the support.

3.3 Skewed slabs

The third series of experiments used for the validation consists of skewed slabs failing in shear, subjected to cycled of loading [13]. The slabs have a span length of 3.6 m with the total length adjusted as a function of the skew angle to fit the span length, 2 m in width and 0.3 m thick. Concrete C35/45 is used and steel B500B is used for the reinforcement.

From this series of experiments, nine out of the 15 experiments are used for the validation, as these experiments use the necessary instrumentation for the stop criteria and use the load in the obtuse corner. The varied parameters among the experiments are the skew angle, the effect of precracking, and the reinforcement layout (orthogonal or non-orthogonal).

4 Validation of stop criteria

The proposed shear stop criteria are broadly validated with experiments on reinforced concrete slab strips, reinforced concrete straight slabs, and reinforced concrete skewed slabs, as introduced in the previous section.

For all experiments considered, the stop criteria indicators are calculated, the load at which the stop criterion is reached P_{stop} is registered, and this load is divided by the maximum load in the experiment P_{max} to find the percentage of the maximum load at which a stop criterion is reached. Then, the statistics (average, AVG, standard deviation STD, and coefficient of variation COV) are calculated. The results for I_{CSDT} for the yellow light is given in Table 2 and for the red light in Table 4, and for I_{CSCT} the validation of the yellow light stop criterion is given in Table 3 and of the red light stop criterion in Table 5.

The results in Table 2 show that the performance of the yellow light stop criterion and the uncertainties are comparable throughout the three analyzed series of experiments. For the skewed slabs, the results have higher uncertainties, which can be partially explained by the fact that the measurements are taken right outside of the recommended range for $M/Vd\times(1/\lambda)$ for the yellow light stop criterion (at lower values). The average value of P_{stop}/P_{max} is in line with the expected value for a yellow light stop criterion (around 50% of the failure load) and the associated coefficient of variation is low, indicating adequate performance of this stop criterion in laboratory conditions.

Table 3 compiles the information on the yellow light stop criterion I_{CSCT}. The overall results are quite similar to the findings for the yellow light stop criterion I_{CSDT}. Indeed, for certain cases I_{CSDT} performs better, whereas for other cases I_{CSCT} gives better results. As such, it is recommended to use both stop criteria for the yellow light criterion, as these are based on different mechanical models, and thus unearth different aspects of the shear behavior. For the beams and skewed slabs, the I_{CSCT} stop criterion is less conservative than I_{CSDT}. For the skewed slabs, this observation can be explained by the lower range of $M/Vd\times(1/\lambda)$ of the measurement.

Table 2. Validation of yellow light stop criterion I_{CSDT}, showing average value of load at which stop criterion is reach to failure load (AVG), standard deviation (STD), and coefficient of variation (COV)

Series of experiments	AVG [%]	STD [-]	COV [%]
Slab strips	55	0.10	18%
Slabs	48	0.07	14%
Skewed slabs	67	0.19	29%

Table 3. Validation of yellow light stop criterion I_{CSCT}.

Series of experiments	AVG [%]	STD [-]	COV [%]
Slab strips	77	0.13	16%
Slabs	43	0.09	21%
Skewed slabs	76	0.13	18%

For the red light stop criterion, Table 4 contains the results for I_{CSDT}. It can be seen that the stop criterion has a lower threshold (lower percentage at which the stop criterion is reached) for straight and skewed slabs than in beams, as evidenced by the slightly lower average values for the slab members. This observation can be explained by the redistribution capacity in slab members, which does not occur in beam members. The coefficient of variation is generally similar for the three studied cases, although on larger for the skewed slabs, where the effect of skewness increases the uncertainties on the shear capacity. The average value is in line with the expectation of a red light stop criterion, allowing for an additional margin of safety during the execution of a proof load test. Considering the nature of the problem (indicators of shear prior to failure), the values of the coefficient of variation are good for shear as they are less than 20%.

The last set of data is given in Table 5, showing the performance of the red light stop criterion I_{CSCT}. For this dataset, the stop criterion works well for the beams and the skewed slabs, and appears to be more conservative for the slab members. Indeed, the average value of the slab experiments is lower than for the two other cases and the coefficient of variation is slightly higher. This observation underlines the need to combine two indicators for stop criteria that are based on different mechanical models, so that the can serve as complimentary stop criteria and capture different shear effects. The I_{CSCT} stop criterion has a low coefficient of variation for the three studied situations. Improvements for the stop criteria for slabs can also be sought that better address the redistribution aspect.

Table 4. Validation of red light stop criterion I_{CSDT}.

Series of experiments	AVG [%]	STD [-]	COV [%]
Slab strips	80	0.12	13%
Slabs	67	0.09	13%
Skewed slabs	61	0.11	18%

Table 5. Validation of red light stop criterion I_{CSCT}.

Series of experiments	AVG [%]	STD [-]	COV [%]
Slab strips	88	0.08	12%
Slabs	44	0.06	15%
Skewed slabs	76	0.10	14%

5 Discussion

The resulting traffic light system gives a broader tool to the bridge engineer to make decisions during a proof load test. As such, this holistic approach is a step forward in the interpretation of structural responses during proof load testing, opening up possibilities for better-informed load tests. Nevertheless, a number of topics still require further research, and the proposed set of stop criteria need to be validated in the field, ideally with a proof load test followed by a collapse test.

As compared to the stop criteria that were used when the research on shear stop criteria was initiated [14], the proposed shear stop criteria form a significant step forward. For the stop criteria from ACI 437.2M-13 [15] and the German guidelines [16] that were originally taken as a reference, the range of values at which the recommended set of stop criteria were achieved was large. Using the Ruytenschildt beams [17] for example, the range of P_{stop}/P_{max} for ACI 437.2M-13 was 0.18 – 0.55, with a number of stop criteria not achieved during the load test, and for the German guideline the range of P_{stop}/P_{max} was 0.18 – 0.98.

Traditionally, stop criteria have been linked to the elastic response of the structure, and serve to avoid irreversible damage. However, a clear threshold of elastic response cannot always be observed, especially when the failure mode of shear is concerned. Therefore, a traffic light system to understand the consequences of further loading the structure has been developed.

Two main improvements have been made with this research. Firstly, the uncertainties on the stop criteria have been significantly reduced, with coefficients of variation between 12% and 21% (and one outlier of 29%, for the case where the stop criteria is applied outside of the intended $M/Vd\times(1/\lambda)$ region). It is important to stress that these values for the coefficient of variation are encouraging, given the fact that: 1) the considered failure mode is shear, and 2) we are aiming at capturing effects of shear failure prior to the failure, further complicating the mechanics at work.

Secondly, by moving from stop criteria to a traffic light system of stop criteria, we achieve two major steps forward. The first advancement is that we are now able to interpret the stop criteria in terms of various potential consequences of loading, from green light (potential serviceability issues and remaining cracking), via yellow light (intermediate warning that more attention needs to be paid to the bridge performance at the next load levels), to red light (further loading can result in a local failure). The second advancement is that a broader set of criteria, associated with various traffic light levels, gives us further information during the test, while the number of additional measurements is modest.

In terms of theoretical aspects, open questions that remain to be addressed deal with 1) the effect of continuity near the support and its effect on the shear capacity of members, as well as the effect on the stop criteria, 2) further analysis of the waviness of the crack profile in the width direction in wide concrete members, 3) bar curtailments and their effect on the shear capacity via the anchorage length, and thus on the stop criteria, 4) the behavior of very skewed members. Moreover, further integration of nonlinear finite element models for the interpretation of the structural responses and developing field-validated numerical models, can be further explored.

6 Summary and conclusions

This paper proposes a set of stop criteria for the proof load testing of reinforced concrete solid slab bridges, failing in shear and flexure. The set of stop criteria are organized into a traffic light system: green light (related to the serviceability limit state), yellow light (related to an intermediate safety level) and red light (related to potential local collapse). The stop criteria encompass a broad range of indicators: both mechanics-based stop criteria for shear (related to the Critical Shear Displacement Theory and the Critical Shear Crack Theory) and flexure (based on sectional analysis and the strain profile, as well as an analysis of cracking), global indicators of bridge behaviour that are more qualitative in nature, indicators using acoustic emission measurements, and indicators for the Serviceability Limit State.

The proposed shear stop criteria have been validated with tests selected from three series of experiments. Overall, it is found that the stop criteria for shear perform as expected. The developed stop criteria for shear also show that measuring at the correct location is critical, and that further experiments for validating the observations can be recommended; in particular, a validation on a real bridge is still necessary.

Ultimately, this research is a step forward in the development of a robust set of stop criteria for use during proof load testing. By using a traffic light system, the bridge engineer is equipped with more information during the load test, so that informed decisions can be made.

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