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Development of Stop Criteria for Proof Loading

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ABSTRACT: Proof loading of bridges is an option to study existing bridges when crucial information is lacking. When proof loading is chosen, the question arises which maximum load should be attained during the test to demonstrate sufficient capacity, and which criteria, the "stop criteria", based on the measurements during the test, would indicate that the test needs to be aborted before reaching the maximum desired load. A review of the literature identifies the stop criteria in currently used codes and guidelines. Beams sawn from the Ruytenschildt bridge were tested in a controlled way in the laboratory and analyzed with regard to the stop criteria from the literature. Recommendations are given for the future development of stop criteria for flexure and shear. These recommendations will form the basis for a guideline on proof loading of existing concrete bridges that is under development in The Netherlands.

1 INTRODUCTION

In the Netherlands many bridges were built in the decades after the Second World War. These structures are now approaching the end of their original service life. As a result, the capacity of over 2000 existing bridges is under discussion. Rehabilitating or replacing all bridges whose capacity is insufficient according to the current codes, while their "real" structural capacity might be sufficient, is not an economical practice. Therefore, other methods are sought to demonstrate the capacity of existing bridges.

One way is by improving the conservative models used in the codes. For the shear assessment of reinforced concrete slab bridges, recommendations have been formulated (Lantsoght et al., 2013a) based on experiments (Lantsoght et al., 2013b, Lantsoght et al., 2014, Lantsoght et al., 2015).

Another way to determine the capacity of existing bridges, is by carrying out proof loading tests. Proof loading can study the capacity when crucial information about the structure is lacking. This information could be related to the material (e.g. the effect of alkali-silica reaction or other material degradation mechanisms on the structural capacity), related to the reinforcement (e.g. when no as-built plans are available) as well as to the structural system (e.g. the effect of restraints at the supports or transverse redistribution capacity). When proof loading, the question arises which maximum load should be attained during the experiment to prove sufficient capacity of the bridge, and which measurement criteria indicate that the proof loading needs to be aborted before reaching the maximum desired load (the so-called stop criteria). In fact, these requirements are contradictory. On one hand, to demonstrate the structural capacity and to gain as much insights on the structural behaviour of the bridge as possible, the proof load should be as high as possible. On the other hand, to prevent irreparable damage and reduction of the structural capacity, the maximum applied load is limited.

This paper studies the stop criteria that are prescribed in the currently available guidelines and compares these to the results of carefully executed experiments. The aim of this research is to contribute to the development of a Dutch guideline for proof loading. The stop criteria should encompass flexure and shear, they should be suitable for existing bridges, and they should not be overly conservative. Overly conservative stop criteria would give the engineers carrying out the proof load test insufficient insight to rate the bridge under study and might lead to unnecessarily low ratings.

2 LITERATURE REVIEW

2.1 *Literature on proof loading*

Over the past few decades, engineers have carried out two types of load tests:

1 diagnostic load tests, to verify the stiffness and behavior of a bridge; and
2 proof load tests, in which a higher load is applied so that a certain capacity can be proven.

Diagnostic proof loading (Russo et al., 2000, Olaszek et al., 2014, Moses et al., 1994, Jauregui et al., 2010, Farhey, 2005) can be used on newly opened bridges to verify the stiffness as well as on existing bridges. Several countries, such as Italy (Veneziano et al., 1984), Switzerland (Bruehwiler et al., 2012) and France (Cochet et al., 2004) require a diagnostic load test upon opening of a bridge. This information is useful, as it can be referred to later on, when on the existing structure a load test is carried out. The effect of material deterioration can then be analyzed based on the reduction in stiffness between the newly opened bridge and the bridge after decades of service life.

Proof loading (Saraf et al., 1996, Moses et al., 1994, Casas and Gómez, 2013, Cai and Shahawy, 2003) is typically carried out on existing brides. The result of a proof load test is a better understanding of the behavior of the bridge, which can be used as input for a probabilistic analysis (Lin and Nowak, 1984, Fu and Tang, 1995, Nowak and Tharmabala, 1988, Hall and Tsai, 1989, Rackwitz and Schrupp, 1985). The change in the probability density function of the capacity side of the equation, R_d, is then as given in Figure 1.

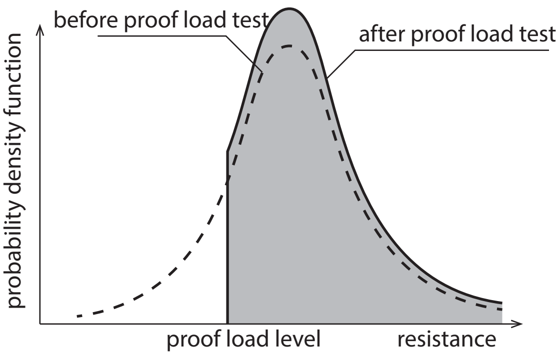

Figure 1. Truncation of probability density function of resistance after proof load test, based on (Nowak and Tharmabala, 1988)

2.2 *Proof loading in The Netherlands*

In The Netherlands, research is carried out on proof loading to determine the required maximum loads in a load test and to determine the stop criteria during a load test. Stop criteria are criteria based on the measurements, which indicate that irreversible damage is inflicted onto the structure, and that further loading is not permitted. Over the past two years, proof load tests have been carried out on the viaduct Vlijmen-Oost (Fennis et al., 2014), on the Halvemaans Bridge (Fennis and Hordijk, 2014) in Alkmaar, on the Ruytenschildt Bridge (Lantsoght et al., 2016), which was not only proof loaded but also tested to failure, and on the viaduct Zijlweg (Koekkoek et al., 2015). The results of these load tests are analyzed and will form the basis for a Dutch guideline on proof loading of bridges.

3 STOP CRITERIA IN CURRENT GUIDELINES

3.1 *German Guideline (Deutscher Ausschuss für Stahlbeton)*

In the German guideline (Deutscher Ausschuss für Stahlbeton, 2000) requirements are formulated that should ensure that proof loading does not lead to irreversible damage to a structure. The stop criteria from the German guideline are the following:

– Concrete compressive strain, ε_c:

$$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0} \tag{1}$$

with ε_c = the strain measured during proof loading; and ε_{c0} = the analytically determined short-term strain in the concrete caused by the permanent loads that are acting on the structure before the application of the proof load and $\varepsilon_{c,lim}$ = the limit value of the concrete strain:

$$\varepsilon_{c,lim} = 0.9\frac{f_{ck}}{E_c} \tag{2}$$

with f_{ck} = the characteristic cylinder concrete compressive strength and E_c = the modulus of elasticity of concrete without long-term effects.

– Strain in reinforcement steel: ε_{s2}:

$$\varepsilon_{s2} < 0.7\frac{f_{ym}}{E_s} - \varepsilon_{s02} \tag{3}$$

with f_{ym} = the average yield strength of steel on the tension side of the cross-section; E_s = the modulus of elasticity of reinforcing bars; ε_{s2} = additional steel strain during experiment: directly measured or derived from other measurements and ε_{s02} = analytically determined strain (assuming cracked conditions) in the reinforcement steel caused by the permanent loads that are acting on the structure before the application of the proof load. When the stress-strain relationship is fully known, the following can be assumed:

$$\varepsilon_{s2} < 0.9\frac{f_{0,01m}}{E_s} - \varepsilon_{s02} \tag{4}$$

with $f_{0,01m}$ = the average strength at a strain of 0.01% (limit of elasticity).

Crack width, w, and increase in crack width, Δw: The requirements from

– Table 1 have to be fulfilled.
– Deflection:

In the cracked state: indications of nonlinear behavior based on the measurements, or if more than 10% permanent (plastic) deformation is found after removal of the load.

Additional stop criteria that are mentioned by the German guideline are:

- Critical changes in the structure reflected by the measurements (for example: load-deflection curve or acoustic emission measurements), which are expected to cause damage when the load is further increased;
- the stability of the structure is endangered;
- critical displacements occur at the supports.

Table 1. Requirements for crack width for newly developing cracks and increase in crack width for existing cracks.

	During proof loading	After proof loading
Existing cracks	$\Delta w \leq 0.3$ mm	$\leq 0.2\Delta w$
New cracks	$w \leq 0.5$ mm	$\leq 0.3w$

3.2 *ACI 437.2M-13*

In ACI 437.2M-13 (ACI Committee 437, 2014) the stop criteria for testing buildings are given (called "acceptance criteria" in this code):

- evidence of failure is not acceptable;
- if the deflections become larger than calculated beforehand, a licensed design professional needs to decide upon the continuation of the test;
- the licensed design professional evaluates the cracks and decides upon continuation of the test;
- if cracks indicate an imminent shear failure, the member is considered as failed;
- if a series of short cracks inclined or parallel to the axis of the reinforcement appear in the region of anchorage and lap splices, the licensed design professional decides upon the continuation of the test;
- if the serviceability limit state (SLS load combination) is studied, deflections, crack spacing and crack widths under the serviceability limit state load have to be recorded and compared to limit values. If the limit values are exceeded, the licensed design professional shall decide upon the continuation of the test;
- deflection limits for monotonic loading (see Figure 2a): the residual deflection, Δ_r, and maximum deflection measured during the test, Δ_l, have to fulfill:

$$\Delta_r \leq \frac{\Delta_l}{4} \tag{5}$$

$$\Delta_l \leq \frac{l_t}{180} \tag{6}$$

with l_t = the span length. If Δ_l is less than 1.3 mm or $l_t/2000$, the requirement for Δ_r from Eq. (5) can be waived.

- deviation from linearity index for cyclic loading (see Figure 2b): the stop criterion for the deviation from linearity index, I_{DL}, is as follows:

$$I_{DL} = 1 - \frac{\tan(\alpha_i)}{\tan(\alpha_{ref})} \leq 0.25 \tag{7}$$

with $\tan(\alpha_i)$ = the secant stiffness of any point i on the increasing loading portion of the load-deflection envelope, and $\tan(\alpha_{ref})$ = the slope of the reference secant line for the load-deflection envelope. The reference line is determined from the first load cycle.

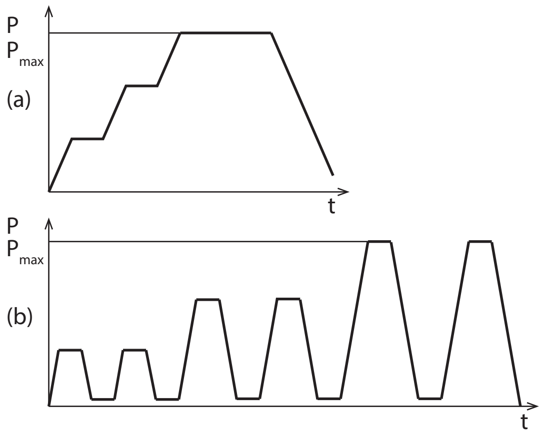

Figure 2: Loading protocols: (a) monotonic loading; (b) cyclic loading.

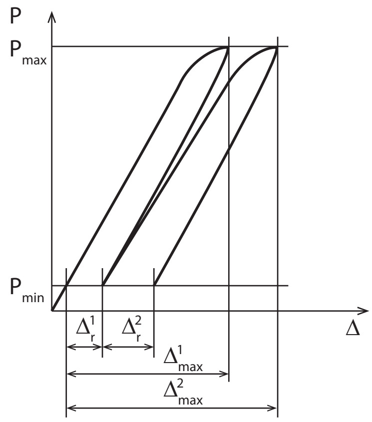

Figure 3: Scheme of load-deflection diagram for two cycles at the same load level, based on ACI 435.2M-13.

- permanency ratio for cyclic loading: the stop criterion from the permanency ratio, I_{pr}, is as follows:

$$I_{pr} = \frac{I_{p(i+1)}}{I_{pi}} \leq 0.50 \tag{8}$$

with I_{pi} and $I_{p(i+1)}$ the permanency indexes for the ith and $(i+1)$th load cycles at the same load level:

$$I_{pi} = \frac{\Delta_r^i}{\Delta_{\max}^i} \tag{9}$$

$$I_{p(i+1)} = \frac{\Delta_r^{(i+1)}}{\Delta_{\max}^{(i+1)}} \tag{10}$$

The definitions of the deflections are as given in Figure 3. I_{pr} is only determined for pairs of load cycles.
- residual deflection for cyclic loading: The residual deflection, with Δ_r measured at least 24 hours after removal of the load, has to fulfill Eq. (5).
- Requirements for retesting for cyclic loading are also given in ACI 437.2M-13.

If a building does not satisfy these stop criteria, it will be used at a lower load rating following the results from the load test or structural analysis.

4 DESCRIPTION OF EXPERIMENTS

4.1 *Introduction*

The Ruytenschildt bridge (Lantsoght et al., 2016) was proof loaded and tested to failure in August 2014. After proof loading and testing to failure of two spans of the Ruytenschildt bridge, beams sawn from another span were tested in a controlled way in the laboratory. The results of these beams have been analyzed with regard to the stop criteria as defined by the currently used codes and guidelines.

4.2 *Material properties*

In total, 31 cores were drilled from the beams after testing, resulting in an average cube compressive strength of f_{cm} = 63 MPa, which corresponds to a cylinder compressive strength of $f_{cm,cyl}$ = 52 MPa. The cores were taken in different directions. On the cores, the thickness of the asphalt layer was measured as 51 mm.

Reinforcement steel QR24 was used, with a characteristic yield strength f_{yk} = 240 MPa. Tensile tests on steel samples taken from the Ruytenschildt bridge showed an average yield strength f_y = 352 MPa and an average tensile strength f_t = 435 MPa for the bars with a diameter φ of 12 mm and f_y = 309 MPa and f_t = 360 MPa for φ = 22 mm. The samples were taken from the bridge after testing, so that yielding of the steel could have occurred before determining the material properties. Past testing of QR24 steel from a similar bridge gave f_y = 283 MPa (Yang et al., 2010).

4.3 *Geometry of the sawn beams*

Three beams, RSB01-RSB03, of 6 m were sawn from the Ruytenschildt bridge. The intended width of the specimens was 500 mm for RSB01 and RSB02 and 1000 mm for RSB03. The coarse action of sawing the beams made that these turned out to be wider than expected. The actual cross-sections of the specimens were measured at five positions and the resulting cross-sections are given in Figure 4.

The asphalt layer was kept on the specimens. This layer was only removed at the loading plate (except for RSB03A) and the top surface was leveled with high strength mortar. This treatment ensures that the poor mechanical properties of the asphalt will not influence the loading process. On the remaining parts of the beam, the asphalt layer was kept to maintain the flexural stiffness of the original bridge.

The position and amount of reinforcement is checked carefully. The positions of the supports are determined so that sufficient anchorage of the reinforcement is guaranteed and anchorage failures during the experiments are avoided. The sectional and reinforcement properties of the beams are given in Table 2.

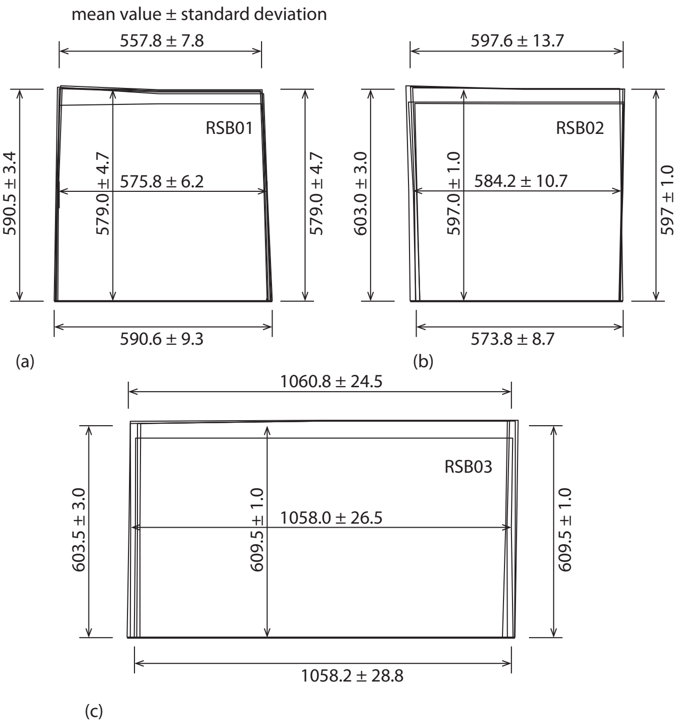

Figure 4. Measured cross-sections of beams: (a) RSB01; (b) RSB02 and (c) RSB03. (Yang, 2015)

Table 2. Properties of critical cross-sections of the beams.

RSB	01F	02A	02B	03F	03A
d (mm)	503	515.5	520	521	515
A_c (m^2)	0.290	0.297	0.307	0.596	0.537
Rebar	4Ø22	4Ø22	4Ø22	9Ø22	7Ø22
	4Ø19	4Ø19	5Ø19	8Ø19	8Ø19
ρ_l	0.91%	0.89%	0.96%	0.95%	0.92%

4.4 *Test setup*

The specimens are simply supported with a span of 5 m, and loaded by a point load. The position of the point load varies according to the type of test. For the bending tests (RSB01F and RSB03F, with “F” for flexural test), the point load is located at midspan. For the shear tests, the loading position is at 1.25 m from the support in RSB02A and RSB02B and at 1.3 m in RSB03A, with “A” or “B” denoting the support close to which was tested.

During the experiments, the magnitude of the load, vertical deflections and crack width were measured. Acoustic emission measurements were used to study crack development and propagation. The loading sequence during the experiments was similar to the cyclic loading protocol as used for proof loading, so that the measurements can be compared with the stop criteria of the available codes and guidelines.

4.5 *Overview of results*

In Table 3, an overview of the experimental results is given. P_u is the maximum load in the experiment. The observed failure mode is given in the last column of Table 3.

RSB01F resulted in a flexural failure, Figure 5a. In both RSB02A and RSB02B, an inclined crack developed in the shear span. The formation of this crack did not result in a drop of the capacity of the specimen. In RSB02B, an inclined crack was observed before yielding of the longitudinal reinforcement. The test was stopped by then to ensure the structural integrity for the test RSB02A. After that, a second test at end B was done as the continuation of RSB02B. The same loading position did not result in a significant additional deflection. Failure then occurred by crushing of the compression strut, indicated by “Shear-Comp” on a second row for RSB02B in Table 3. In RSB03A (Figure 5b), the shear span was increased to 1.3 m, resulting in failure by forming an inclined crack in the shear span.

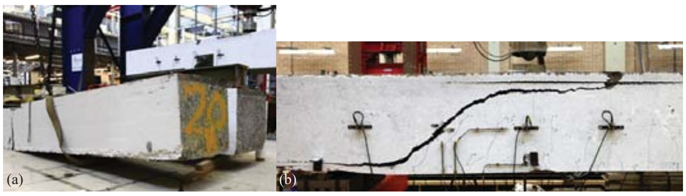

Figure 5: Observed failure modes: (a) RSB01F, flexure; (b) RSB03A: shear.

Table 3. Test results, predicted values for shear and flexure and failure mode.

Test	P_y (kN)	$P_{s,EC}$ (kN)	$P_{s,CSD}$ (kN)	P_u (kN)	*Failure* Mode
RSB01F	275.8	466.8	443.4	275.8	Flexure
RSB02A	376.2	322.5	420.0	368.7	Flexure
RSB02B	423.4	331.2	435.4	415.8	Flexure
				424.2	Shear-Comp
RSB03F	617.3	914.1	889.9	606.6	Flexure
RSB03A	792.0	603.7	783.7	706.7	Flexural shear

A comparison with the predicted shear and flexural capacity is also given in Table 3. P_y is the calculated load at yielding in the critical cross-section. $P_{s,EC}$ is the calculated load for shear failure according to NEN-EN 1992-1-1:2005 §6.2.2 (CEN, 2005), but translated from characteristic values to average values. $P_{s,CSD}$ is the calculated load for shear failure according to the Critical Shear Displacement theory (Yang, 2014). The comparison between experimental and calculated values shows that the prediction of the yielding moment has a difference of less than 3%. Additionally, it was confirmed that beams with plain bars have large rotational capacities.

5 ANALYSIS OF TEST RESULTS

5.1 *Choice of stop criteria*

The loads at which the stop criteria are exceeded are calculated from the measurements on the beams. Detailed calculations can be found elsewhere (Tersteeg, 2015).

The two guidelines that provide stop criteria, ACI 437.2M-13 (ACI Committee 437, 2014) and the German guideline (Deutscher Ausschuss für Stahlbeton, 2000) are used for the analysis.

The stop criteria that are analyzed according to the German guideline are the criterion for the width of a new crack and the criterion for the residual deflection. Note that the concrete compressive strain were not measured so that the strain criterion from the German guideline cannot be linked to a limiting load in the experiment. Practically it is not often that the bridge owners allow the removal of the concrete cover to measure the strains in the reinforcement steel, so that a stop criterion based on strains is not considered as a practical criterion.

The stop criteria that are analyzed based on ACI 437.2M-13 are all quantifiable stop criteria (or, acceptance criteria as used in ACI 437.2M-13). The residual deflection after each load cycle, permanency ratio and deviation from linearity are all studied.

5.2 *RSB01*

In Table 4, a comparison between the loads at which the stop criteria would be exceeded ($P_{ACI,st}$ for ACI 437.2M-13 and $P_{DA,st}$ for the German guideline from DAfStB) and the maximum observed load in experiment RSB01F are compared. For both methods, the residual deformation, Δ_r, is governing. The stop criteria are exceeded well before failure occurs in the experiment: at 27% of the maximum load for ACI 437.2M-13 and at 18% for the German guideline.

Table 4. Comparison between stop criteria from ACI 437.2M-13 and DAfStB and test RSB01F.

ACI 437.2M-13 Criterion	Load (kN)	DAfStB Criterion	Load (kN)
Δ_r	75	Δ_r	50
I_{pr}	75	w new crack	275
I_{DL}	100	Strain	-
$P_{ACI,st}$	75	$P_{DA,st}$	50
P_u	275.8	P_u	275.8
$P_{ACI,st}/P_u$	0.27	$P_{DA,st}/P_u$	0.18

5.3 *RSB02*

As introduced before, two experiments were carried out on RSB02: RSB02A and RSB02B. The comparison with the loads at which the stop criteria are exceeded are given in Table 5 for RSB02A and Table 6 for RSB02B. For RSB02A, the requirements for Δ_r according to ACI 437.2M-13 are exceeded during the final load step, so the maximum load is indicated as 250 kN – 368 kN, the range of the final load step to failure. The permanency ratio I_{pr} was not exceeded during the experiment. For RSB02B, the load for which the requirement for Δ_r from ACI 437.2M-13 is exceeded is when the retesting of RSB02 at support B is considered as a new experiment.

Table 5. Comparison between stop criteria from ACI 437.2M-13 and DAfStB and test RSB02A.

ACI 437.2M-13 Criterion	Load (kN)	DAfStB Criterion	Load (kN)
Δ_r	250-368	Δ_r	225
I_{pr}	$>P_u$	w new crack	175
I_{DL}	175	Strain	-
$P_{ACI,st}$	175	$P_{DA,st}$	175
P_u	368.7	P_u	368.7
$P_{ACI,st}/P_u$	0.47	$P_{DA,st}/P_u$	0.47

For RSB02A and B, the stop criteria according to ACI 437.2M-13 and the German guideline are reached during the same load step. For RSB02A, different stop criteria are governing for both methods: the deviation from linearity I_{DL} is governing for ACI 437.2M-13 and the crack width w for new cracks is governing for the German guideline. For RSB02B, the residual deformation is governing for both methods. The stop criteria are exceed well before failure occurs in the experiment: at 47% of the maximum load for RSB02A and at 18% for RSB02B.

Table 6. Comparison between stop criteria from ACI 437.2M-13 and DAfStB and test RSB02B.

ACI 437.2M-13 Criterion	Load (kN)	DAfStB Criterion	Load (kN)
Δ_r	75	Δ_r	75
I_{pr}	175	w new crack	125
I_{DL}	415	Strain	-
$P_{ACI,st}$	75	$P_{DA,st}$	75
P_u	424.2	P_u	424.2
$P_{ACI,st}/P_u$	0.18	$P_{DA,st}/P_u$	0.18

5.4 *RSB03*

As introduced before, two experiments were carried out on RSB03: RSB03F (flexural failure) and RSB03A (shear failure). The comparison with the loads at which the stop criteria are exceeded are given in Table 7 for RSB03F and Table 8 for RSB03A. For RSB03F, the requirement for I_{DL} according to ACI 437.2M-13 is exceeded in the step between 150 kN and 250 kN. I_{DL} increases from 0.4% to 32% in this load step, so with a smaller step size a lower load could be found at which the criterion is exceeded. The permanency ratio I_{pr} was not exceeded during the experiment. For RSB03A, the criteria from ACI 437.2M-13 for Δ_r and I_{pr} are not exceeded and from the German guideline the criterion for Δ_r is not exceeded. The load of 690 kN corresponding to the criterion for w for a new crack according to the German guideline is determined based on ignoring values below 0.003 mm, related to the accuracy of the LVDTs that were used. If measurements below 0.003 mm are taken into account, the load at which the criterion is exceeded would be 200 kN.

For RSB03F, the deviation from linearity, I_{DL}, is the governing stop criterion according to ACI 437.2M-13 and the residual deformation, Δ_r, is governing according to the German guideline. The stop criteria are exceeded well before failure occurs in the experiment: at 41% of the maximum load for the stop criteria of ACI 437.2M-13 and at 25% for the German guideline.

Table 7. Comparison between stop criteria from ACI 437.2M-13 and DAfStB and test RSB03F.

ACI 437.2M-13 Criterion	Load (kN)	DAfStB Criterion	Load (kN)
Δ_r	340	Δ_r	150
I_{pr}	$>P_u$	w new crack	300
I_{DL}	250	Strain	-
$P_{ACI,st}$	250	$P_{DA,st}$	150
P_u	606.6	P_u	606.6
$P_{ACI,st}/P_u$	0.41	$P_{DA,st}/P_u$	0.25

For RSB03A, the only test that failed in shear, the stop criteria do not lead to satisfactory results. According to ACI 437.2M-13, I_{DL} is the governing stop criterion and according to the German guideline, w for a new crack is governing. The stop criteria are not reached well in advance of reaching failure: according to ACI 437.2M-13 only one stop criterion is achieved, at 55% of the maximum load, and according to the German guideline only one stop criterion is achieved as well, at 98% of the maximum load. In other words, for this shear test, the German guideline would not have warned against imminent failure.

Table 8. Comparison between stop criteria from ACI 437.2M-13 and DAfStB and test RSB03A.

ACI 437.2M-13 Criterion	Load (kN)	DAfStB Criterion	Load (kN)
Δ_r	$>P_u$	Δ_r	$>P_u$
I_{pr}	$>P_u$	w new crack	690
I_{DL}	390	Strain	-
$P_{ACI,st}$	390	$P_{DA,st}$	690
P_u	706.7	P_u	706.7
$P_{ACI,st}/P_u$	0.55	$P_{DA,st}/P_u$	0.98

6 RECOMMENDATIONS

From the comparison between the load at which the stop criteria are exceeded in a cyclic loading test and the maximum load at which failure occurs, it can be seen that the stop criteria are exceeded well before reaching the maximum load when the failure mode is flexure. However, for shear failure, new stop criteria need to be developed.

For flexure, the failure criteria that can be used and modified, if necessary, are:

- The crack width criterion from the German guideline: this criterion was governing in one experiment and achieved before failure in all flexural experiments. Limiting the crack width also has practical applications: the residual crack width after a proof load test needs to be limited for durability reasons. A lower bound for the residual crack width should be included as well. Small cracks never close completely because of debris filling the crack after unloading. As such, the residual crack width criterion could be exceeded even when no physical damage is present.
- The criterion for residual deflection, where either the limit value from ACI 437.2M-13 or the German guideline can be taken as the maximum residual deflection: the limit value from the German guideline was governing in three of the tests in which flexural failure was achieved. The limit value from ACI 437.2M-13 is governing in two experiments on beams in flexure. However, in a proof load test, always a minimum load level (typically 10% of the intended maximum load that will be applied) has to be maintained between the cycles. To calculate the residual deflection, no load should be present. Therefore, the criterion will have to be adapted so that the deflection at the load of a given load step can be compared to the base line load instead of to a load of 0 kNThe criterion for the deviation from linearity index from ACI 437.2M-13: this criterion is consistently exceeded before reaching the maximum load in each experiment (both flexure and shear). Only for RSB02B, during retesting of the beam, the criterion was achieved at 98% of the maximum load, which indicates insufficient warning potential. Therefore, this criterion could be less suitable for existing bridges in which the reinforcement has yielded or in which significant cracks caused by, for example, alkali-silica reaction are present. The adaptation of this criterion is subject of future research.

The further development of the stop criteria for shear and flexure for the Dutch guideline for proof loading is subject of future research.

7 SUMMARY AND CONCLUSIONS

Load testing of bridges is a way to gain more insight in their structural behavior. Diagnostic proof loading to low load levels to check the stiffness of a structure is possible, as well as proof load testing, in which a certain load level needs to be achieved to proof sufficient capacity. In proof loading, the maximum load to approve a bridge needs to be determined as well as the stop criteria. These criteria indicate when a proof load test needs to be aborted because permanent damage can be inflicted upon the structure, or because failure might be imminent. In the Netherlands, proof loading is studied for the assessment of existing bridges.

A literature review has identified the existing codes and guidelines for load testing: the German guideline, ACI 437.2M-13, the French guideline, the British guideline, the Manual for Bridge Rating through Load Testing and the Irish guideline NRA BA54:2014. Only the German guideline and ACI 437.2M-13, which is developed for buildings and cannot be used for bridges without adaptations, have clearly defined stop criteria as part of the provisions. The German guideline defines stop criteria based on strains in the concrete and steel, crack width and increase in crack width, and residual deflection. ACI 437.2M-13 defines stop criteria based on the comparison with calculated deflections, signs of shear or anchorage failure, residual deflection, the deviation from linearity index and the permanency ratio.

Three beams were sawn from a bridge, the Ruytenschildt bridge, and five tests were carried out on these beams. The material properties and geometry were studied. Cyclic loading was applied to evaluate the stop criteria from the German guideline and ACI 437.2M-13. This analysis was carried out based on the loads at which the stop criteria are exceeded. For flexure, the stop criteria for both methods are exceeded well before failure. For shear, other stop criteria should be formulated.

For the development of a Dutch guideline for proof loading, new stop criteria for shear are necessary. For flexure, the criteria for the residual deflection, the crack width and the deviation from linearity index should be revised so that the improved stop criteria are not too conservative for structures with existing cracks and possible yielding of the reinforcement. At the same time, the improved stop criteria will have to ensure safe execution of proof load tests.

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