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Stop criteria for proof load tests verified with field and laboratory testing of the Ruytenschildt Bridge

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Abstract

As the existing bridge stock is aging, improved assessment methods such as proof load testing become increasingly important. Proof load testing involves large loads, and as such the risk for the structure and personnel can be significant. To capture the structural response, extensive measurements are applied to proof load tests. Stop criteria, based on the measured quantities, are used to identify when further loading in a proof load test is not permitted. For proof load testing of buildings, stop criteria are available in existing codes. For bridges, recently stop criteria based on laboratory tests on beams reinforced with plain bars have been proposed. Subsequently, improved stop criteria were developed based on theoretical considerations for bending moment and shear. The stop criteria from the codes and the proposed stop criteria are compared to the results from field testing to collapse on the Ruytenschildt Bridge, and to the results from laboratory tests on beams sawn from the Ruytenschildt Bridge. This comparison shows that only a small change to the stop criteria derived from laboratory testing is necessary. The experimental evidence strengthens the recommendation for using the proposed stop criteria in proof load tests on bridges for bending moment, whereas further testing to confirm the stop criteria for shear is necessary.

Keywords: concrete bridges; field testing; flexure; laboratory experiments; measurements; proof load testing; reinforced concrete; sensors; shear; slabs.

1 Introduction

In Europe and North America, the existing bridge stock is aging rapidly. As such, methods for assessment and evaluation of existing bridges become increasingly important. In the Netherlands, a large number reinforced concrete slab bridges need to be assessed (1) as a result of changes in the codes. When the uncertainties are large, field testing can be used to improve the assessment (2). Possible sources for the uncertainties may be: lack of structural plans (3), the structural behavior (4), or the effect of material degradation on the capacity (5, 6). In a proof load test (7), a load representing the factored live loads is applied to the bridge. The test is used to directly demonstrate that the bridge fulfils the code requirements.

For load testing of structures, a number of guidelines are available. For bridges, the Manual for Bridge Evaluation (8), based on the Manual for Bridge Rating through Load Testing (9), provides recommendations for diagnostic load tests and for finding the target proof load in a proof load test, but no stop criteria are defined. For buildings, the German guideline (10) and ACI 437.2M-13 (11) prescribe the loading protocol and stop criteria. The German guideline (10) describes stop criteria for the concrete strain, the steel strain, the maximum and residual crack width for new and existing cracks, and residual deformation. ACI 437.2M-13 describes acceptance criteria that are linked to the loading protocol (monotonic or cyclic loading protocol). For the cyclic loading protocol, the acceptance criteria are residual deflection, permanency ratio, and deviation from linearity index. For the assessment of existing bridges, it is important to develop stop criteria for flexure and shear (12, 13). None of the existing codes permits the proof load testing of fracture- and shear-critical bridges. A proposal based on experiments on beams with plain bars cast in the laboratory was developed (14). A distinction was made between sections previously cracked in bending and uncracked sections, and between the failure modes of shear and flexure.

2 Experiments

2.1 Ruytenschildt field test

The Ruytenschildt Bridge (15), see Figure 1, had to be replaced for functional reasons, and as such was available for a field test to collapse. This bridge was a five-span reinforced concrete slab bridge with a skew angle of 18°, cast integrally to the abutments and built in 1962. Each span was 9 m long. The width of the part of the bridge (related to the staged demolition and replacement process) that could be tested to collapse was 7.365 m. The thickness was constant at 550 mm. The average cube compressive strength was determined on cores as f_{cm} = 64 MPa. Plain bars of steel type QR24 were used. This reinforcement has a measured yield strength of f_{ym} = 282 MPa.

During the test, the load was applied at the critical position for slabs failing in shear, at a clear face-to-face distance between the load and the support of $a_v = 2.5d_l \approx 1250$ mm and in the obtuse corner with an edge distance of 800 mm in the first span and 600 mm in the second span. Four concentrated loads of 400 mm × 400 mm, organized in the same way as a single tandem from NEN EN 1991-2:2003 (16) were applied in the field tests. The load was applied through a system of jacks, under a steel spreader beam loaded with counterweights. A cyclic loading protocol was used, and an extensive sensor plan was applied during the test. The maximum applied load in span 1 was 3049 kN, and in span 2 3991 kN. In span 1, no failure was achieved, but flexural distress was observed. The failure mode in span 2 was flexural failure (defined as the development of yielding in the reinforcement; loading was not continued until crushing of the concrete was achieved), combined with a settlement of the pier of 8 mm after delayed recovery.

Figure 1. Picture of the Ruytenschildt Bridge.

2.2 Ruytenschildt beams

Further testing of three beams sawn from the bridge was carried out in the laboratory (17). The three beams, named RSB01 through RSB03, had a length of 6 m and a width of 500 mm for RSB01 and RSB02 and of 1000 mm for RSB03. Since the beams were sawn from the bridge deck, the resulting cross-sections were rather irregular. A layer of asphalt of 50 mm was present on the beams, and was only removed on the position of the load. The width of the support was 100 mm and the size of the loading plate was 300 mm × 300 mm.

An overview of the properties of the beams and the critical cross-sections, as well as the maximum load and failure mode, is given in Table 1. The average values of the width and height measured at different positions along the beam are given in Table 1. All experiments were carried out in a cyclic way so that all stop criteria could be verified.

Table 1. Overview of properties of tested beams

Property	RSB01F	RSB02A	RSB02B	RSB03F	RSB03A
d_l (mm)	503	515.5	520	521	515
A_c (m^2)	0.290	0.297	0.307	0.596	0.537
b_{avg} (mm)	575.8	584.2	584.2	1058.0	1058.0
h_{avg} (mm)	579.0	597.0	597.0	609.5	609.5
Rebar	4Ø22 4Ø19	4Ø22 4Ø19	4Ø22 5Ø19	9Ø22 8Ø19	7Ø22 8Ø19
ρ_l	0.91%	0.89%	0.96%	0.95%	0.92%
P_u (kN)	275.8	368.7	415.8	606.6	706.7
Failure mode	Flexure	Flexure	Flexure	Flexure	Flexural shear

3 Analysis of stop criteria

3.1 Ruytenschildt field test

Table 2. Load P_{lim} for which stop criteria of German guideline are exceeded on Ruytenschildt Bridge

Criterion	P_{lim} (kN) Span 1	P_{lim} (kN) Span 2
Strain	2719	3028
Increase in crack width	$>P_u$	$>P_u$
Residual crack width	481	418
Residual deformation (measured)	408	221
Residual deformation (zero)	474	3156

First, the stop criteria of the German guideline (10) are compared to the measurements obtained during the two experiments on the Ruytenschildt Bridge. An overview of the results is given in Table 2. The residual deformation is evaluated in two ways: as the measured residual deformation (while the baseline load level is still acting), and as the calculated value that would be found for a load of 0 kN if the stiffness of the unloading branch is used to find the extrapolated value. For the test on the first span, it seems that only the stop criterion with regard to a limiting strain fulfils its purpose. The stop criterion with regard to the increase in crack width is never exceeded, whereas the stop criteria with regard to residual crack width and deformation are exceeded during the first load level. For the test in the second span, similar observations can be made. Additionally, the stop criterion based on the calculated residual deformation for a load of 0 kN seems to work well in the second span, but did not lead to trustworthy results in the first span.

Table 3. Load P_{lim} for which stop criteria of ACI 437.2M-3 are exceeded on Ruytenschildt Bridge

Criterion	P_{lim} (kN) Span 1	P_{lim} (kN) Span 2
I_{DL}, loading branch	1438	418 / 3156
I_{DL}, unloading branch	1923	418 / 2657
I_{pr}	481	444
Residual deformation (measured)	780	3738
Residual deformation (zero)	$>P_u$	3738

The acceptance criteria of ACI 437.2M-13 (11) for a cyclic loading protocol are evaluated next. These stop criteria are developed to be used together with the cyclic loading protocol prescribed in ACI 437.2M-13, which is not the same as what was used in the experiments on the Ruytenschildt Bridge. An overview of the results is given in Table 3. The value of the deviation from linearity index was evaluated in the loading and unloading branch, to see if the effect of cracking in the loading branch is important for this stop criterion. The difficulty in applying the stop criterion from the permanency ratio I_{pr} is that the applied load has to be exactly the same across the different load cycles. This requirement was not achieved in the tests on the Ruytenschildt Bridge because of the chosen execution method, so that large deviations on the values of I_{pr} occurred. The residual deflection should be determined 24 hours after removing the load. However, for field testing of bridge, where all delays mean obstructions for the traveling public, it is not possible to wait 24 hours to take the final measurement of the residual deflection. For the second span, the value of the stiffness changed considerably from the first to the second cycle, so that the value of I_{DL} was determined based on the first cycle (P_{lim} = 418 kN) as well as based on the second cycle (P_{lim} = 3156 kN for the loading branch and P_{lim} = 2657 kN for the unloading branch). From the results in Table 3 it can be seen that the stop criteria from ACI 437.2M-13 do not lead to good results for the application to the experiments on the Ruytenschildt Bridge. As mentioned before, one of the main reasons for this observation is that the prescribed loading protocol for buildings from ACI 437.2M-13 was not suitable for the field tests on the Ruytenschildt Bridge.

Table 4. Load P_{lim} for which proposed stop criteria are exceeded on Ruytenschildt Bridge

Criterion	**P_{lim} (kN) Span 1**	**P_{lim} (kN) Span 2**
Concrete strain	2719	3028
Maximum crack width	$>P_u$	$>P_u$
Residual crack width	$>P_u$	$>P_u$
Stiffness reduction (5%), loading branch	481	444
Stiffness reduction (5%), unloading branch	481	1492
Stiffness reduction (25%), loading branch	1923	3159
Stiffness reduction (25%), loading branch	1949	3159
Deformation profiles – longitudinal	1900	2600
Deformation profiles - transverse	1900	2600

In a last step, the proposed stop criteria from beam experiments (14) are evaluated with the results from the tests on the Ruytenschildt Bridge. Whereas the tests on the Ruytenschildt bridge were designed to possibly create a shear failure, the actual failure mode in the experiments was a flexural failure. The structure was cracked in bending after many decades in service. The stop criteria for a cracked structure are revised here, both for shear and flexure, to study the effect of the proposed stop criteria with the testing of the Ruytenschildt Bridge. An overview of the results is given in Table 4. The first three stop criteria are the same as for the German guideline, except that crack widths smaller than 0.05 are not considered and that the limit for the maximum crack width is w_{max} = 0.5 mm. When considering the reduction of the stiffness in the loading and unloading branch, see Figure 2, it can be seen that the variation on the results in the first cycles is large. As such, using a reduction of 5% of the stiffness in a load test does not lead to good results as this value lies within the error margin of a field test. Therefore, a maximum stiffness reduction of 25% is analyzed as well, and this value gives better results. The analysis of the deformation profiles is carried out based on plotting the vertical displacements in the transverse and longitudinal direction, and analyzing the resulting plots for changes over the different load levels. An example of the resulting deformation profile is shown in Figure 3. In this profile, it can be seen that the repeatability of the test results becomes less for the subsequent load cycles at the load level of 2600 kN. Based on the results in Table 4, and when using a maximum stiffness reduction of 25% instead of 5%, a proof load test on the Ruytenschildt Bridge would be stopped at 62% of the maximum applied load (not the failure load, as failure was not achieved) in span 1, and at 65% of the failure load in span 2. The proposed stop criteria are thus not overly conservative, but allow for sufficient buffer between the maximum load that can be allowed in a proof load test and the occurrence of failure.

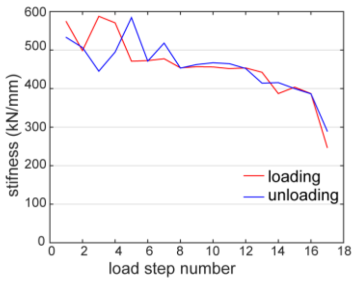

Figure 2. Overview of stiffness per load step, span 1 of the Ruytenschildt Bridge.

3.2 Ruytenschildt beams

In a next step, the experiments carried out on the beams sawn from the Ruytenschildt Bridge are analysed. First, the stop criteria from the German guideline are analyzed, see Table 5. The strain is calculated based on the measurements of the horizontal LVDTs, divided by the length of 150 mm over which the LVDTs are placed. Since this length is limited, the strain measurements are significantly disturbed by local crack development. For the current analysis, the results are used to get an indication of the usefulness of the stop criteria with regard to the concrete strains. The stop criterion with regard to the maximum crack width is hardly ever exceeded during the experiments. The stop criterion with regard to the residual crack width is typically exceeded at the first or second load level. For RSB03A, this stop criterion is not exceeded, but only two LVDTs resulted in good measurements. Finally, the stop criterion with regard to the residual deformation does not seem to lead to good results. This observation can be explained by the fact that the experiments were carried out in a displacement-controlled manner, and not force-controlled. The stop criterion with regard to the residual deformation requires a constant value of the load for its evaluation.

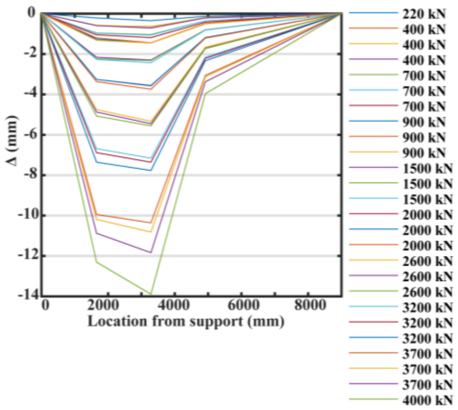

Figure 3. Profile of vertical deflections in the longitudinal direction, span 2 of the Ruytenschildt Bridge

Table 5. Load P_{lim} for which stop criteria of German guideline are exceeded on Ruytenschildt Bridge beams.

Criterion	P_{lim} (kN) RSB01F	P_{lim} (kN) RSB02A	P_{lim} (kN) RSB02B	P_{lim} (kN) RSB03F	P_{lim} (kN) RSB03A
Strain	150	196	219	319	585
Increase in crack width	274	P_u	$>P_u$	P_u	$>P_u$
Residual crack width	77	76	74	147	$>P_u$
Residual deformation (measured)	49	226	74	147	196
Residual deformation (zero)	49	P_u	74	147	P_u

Next, the acceptance criteria given in ACI 437.2M-13 (11) are evaluated. These criteria are developed for use together with the prescribed cyclic loading protocol from ACI 437.2M-13, which is different from the loading protocols used for these experiments. The results are shown in Table 6. In general, the deviation from linearity index I_{DL} gives the same results for the loading and unloading branch, since the beams were sawn from an existing bridge, and were already cracked. The difficulty with evaluating the permanency ratio I_{pr} lies in the fact that it is based on the comparison between two cycles at the same load level, and that the load has to be exactly the same. Since the experiments were carried out in a displacement-controlled manner, this requirement is not fulfilled, and the test results are not very suitable for an evaluation of this stop criterion. The stop criterion with regard to the residual deformation is less conservative than prescribed in the German guideline (25% of the maximum deflection according to ACI 437.2M-13 as compared to 10% in the German guideline). However, since the experiments were carried out in a displacement-controlled manner, the measurements are not entirely suitable for evaluating this stop criterion, which is reflected by the poor results of this criterion in Table 6. Considering these limitation, it can be seen that the stop criteria from ACI 437.2M-13 are not directly suitable to be used together with the Dutch proof load testing practice.

Table 6. Load P_{lim} for which stop criteria of ACI 437.2M-3 are exceeded on Ruytenschildt Bridge beams.

Criterion	P_{lim} (kN) RSB01F	P_{lim} (kN) RSB02A	P_{lim} (kN) RSB02B	P_{lim} (kN) RSB03F	P_{lim} (kN) RSB03A
I_{DL}, loading branch	77	175	$> P_u$	293	390
I_{DL}, unloading branch	77	175	$>P_u$	244	391
I_{pr}	75	126	125	293	196
Residual deformation (measured)	49	P_u	74	147	P_u
Residual deformation (zero)	50	P_u	74	P_u	P_u

Finally, the proposed stop criteria are compared with the experimental results from the tests on the beams sawn from the Ruytenschildt Bridge, see Table 7. Two lasers, lasers 3 and 6, were used under the beam at the position of the load. Since the beams were not sawn straight, the effect of torsion caused different deflections to be measured on both sides of the beam by lasers 3 and 6. Therefore, the results of lasers 3 and 6 are analyzed separately for the stop criterion with regard to the stiffness reduction. On RSB02 and RSB03, both side faces of the beam were instrumented with LVDTs, so that the deformation profiles on the north and south faces can be analyzed separately. These measurement points are relatively close together and cracking disturbs the measurement of the horizontal deformations. Moreover, not in all experiments did all LVDTs lead to good results, so that the plots of the horizontal deformation profiles were often disturbed. When no sensor output was available for the evaluation of the stop criterion, "-" was added in Table 7. The difference between the values for the maximum and residual crack width in Table 5 and Table 7 are caused by the fact that according to the proposed stop criteria all crack widths smaller than 0.05 mm can be considered as equal to 0 mm.

Table 7. Load P_{lim} for which the proposed stop criteria are exceeded on Ruytenschildt Bridge beams.

Criterion	P_{lim} (kN) RSB01F	P_{lim} (kN) RSB02A	P_{lim} (kN) RSB02B	P_{lim} (kN) RSB03F	P_{lim} (kN) RSB03A
Concrete strain	150	196	219	319	585
Max. crack width	274	$> P_u$	$> P_u$	P_u	$> P_u$
Res. crack width	150	226	416	P_u	$> P_u$
Δ*EI* (25%), L, laser 3	77	175	-	-	391
Δ*EI* (25%), UL, laser 3	103	175	-	-	391
Δ*EI* (25%), L, laser 6	274	P_u	$> P_u$	244	P_u
Stiffness reduction (25%), UL, laser 6	150	$>P_u$	$> P_u$	244	391
Def. prof. – horizontal, N	150	225	175	P_u	-
Def. prof. – horizontal, S	-	$> P_u$	175	342	-
Def. prof. – vertical	150	225	175	342	391

L = loading branch, UL = unloading branch

For RSB01F, the first stop criterion that is exceeded is the stop criterion for the stiffness at 28% of the failure load. For RSB02A, the stiffness stop criterion is the stop criterion that is first exceeded, at 47% of the failure load. For RSB02B, the deformation profiles are the stop criterion that is first exceeded, at 42% of the failure load. For RSB03F, the first stop criterion that is exceeded is the criterion related to the stiffness reduction, at 41% of the failure load. For RSB03A, the stop criteria for the stiffness and the vertical displacement are exceeded at the same time, at 57% of the failure load. Seeing these results, it can be said that in general the stop criteria are conservative and exceeded long before failure can be expected. For RSB01F, the stop criteria are exceeded for a very low value of the load. This observation can be explained by the fact that for RSB01F the values of the stiffness were found to fluctuate strongly, possibly caused by the fact that the cross-section was not perfectly rectangular and that torsional distress could occur in the experiment.

4 Discussion

When comparing the results of the experiments in two spans of the Ruytenschildt Bridge in the field and on the beams sawn from the Ruytenschildt Bridge with the available stop criteria, a few points can be highlighted for discussion, and topics for further research can be pointed out. First of all, the performance of the existing stop criteria from the German guideline and ACI 437.2M-13 is not ideal for combination with proof load testing practices. The main limiting factors here are the fact that the proof load tests are carried out in a displacement-controlled manner, so that stop criteria that require a fixed constant value of the load are not very suitable. The second limiting factor is that for the application of ACI 437.2M-13, it is necessary to follow the prescribed cyclic loading protocol. This loading protocol is excellent for the testing of existing buildings, but may not be directly applied to existing bridges.

The proposed stop criteria that were developed based on experiments on beams, were developed precisely to be suitable for the use with proof load testing on existing bridges. These criteria were analyzed with the experimental results of the tests on the Ruytenschildt Bridge and the beams sawn from this bridge. For the field tests, the proposed stop criteria were exceeded between 60% and 70% of the maximum applied load in the experiment. For the laboratory tests, the proposed stop criteria were exceeded between 40% and 60% of the maximum load, except for one test where the results of the stiffness fluctuated strongly and led to an exceedance of the stop criterion for the stiffness at only 28% of the failure load. These observations are valid provided that a stiffness reduction of 25% is used as the stop criterion, instead of a reduction of 5%, as proposed originally. The resulting proposal for stop criteria is then shown in Table 8. In Table 8, ε_c is the measured strain in the concrete, $\varepsilon_{c,lim}$ is the maximum strain (800 $\mu\varepsilon$ for concrete compressive strengths larger than 25 MPa), ε_{c0} is the strain caused by the permanent loads, w_{max} is the maximum crack width in a given load cycle, and w_{res} is the residual crack width at the end of a load cycle.

Table 8. Updated recommendations for stop criteria for proof load testing

	Cracked in bending or not	
Failure mode	**Not cracked in bending**	**Cracked in bending**
Bending moment	$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0}$ $w_{max} \leq 0.5$ mm $w_{res} \leq 0.3 w_{max}$, min 0.05 mm 25% reduction in stiffness Deformation profiles Load-deflection diagram	$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0}$ $w_{max} \leq 0.5$ mm $w_{res} \leq 0.2 w_{max}$, min 0.05 mm 25% reduction in stiffness Deformation profiles Load-deflection diagram
Shear	$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0}$ $w_{max} \leq 0.3$ mm 25% reduction in stiffness Deformation profiles Load-deflection diagram	$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0}$ 25% reduction in stiffness Deformation profiles Load-deflection diagram

One topic that needs further study is the development for stop criteria for shear. The Ruytenschildt Bridge tests did not result in shear failure, and of the beam tests, only one experiment failed in shear. As such, the support for the proposed stop criteria for shear is limited. To validate this criteria, it is strongly recommended to carry out further testing to evaluate the stop criteria for beams failing in shear, both for the case of beams cracked in bending from previous testing and for the case of virgin specimens.

5 Summary and Conclusions

For the assessment of existing bridges, proof load testing can be an interesting option when the uncertainties on the structure are large. In a proof load test, a load representing the factored live load is applied to the bridge. If the bridge can withstand this load without signs of distress, it is shown experimentally that the bridge fulfils the code requirements. As large loads are required for proof load testing, the involved risks can be large, and the structural response most be closely monitored during the test. if the structural response exceeds previously defined bounds, called the "stop criteria", the proof load test must be terminated and further loading is not allowed.

In this paper, the existing stop criteria from the German guideline and ACI 437.2M-13 and proposed stop criteria are verified with experimental data from field and laboratory tests.

The stop criteria from ACI 437.2M-13 are not directly applicable to field testing of bridges, since the cyclic loading protocol of ACI 437.2M-13 must be used together with the stop criteria of this code. For field testing, usually displacement-controlled load application methods are used, so that not all existing stop criteria from the German guideline and ACI 437.2M-13 are suitable. These drawbacks of the existing stop criteria are mitigated by the proposed stop criteria developed on beam tests. These proposed stop criteria are exceeded at 60% to 70% of the maximum applied load in the field tests, which was the failure load for flexure in the second test, and at 40% to 60% of the failure load in the laboratory tests on the beams sawn from the bridge, which failed in for the majority of the tests in flexure and for one single test in shear.

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