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BEAM EXPERIMENTS ON ACCEPTANCE CRITERIA FOR BRIDGE LOAD TESTS

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ABSTRACT

Loading protocols and acceptance criteria are available in the literature for load tests on buildings. For bridges, proof load tests are interesting when crucial information about the structure is missing, or when the uncertainties about the structural response are large. The acceptance criteria can then be applied to evaluate if further loading is acceptable, or could lead to permanent damage to the structure. To develop loading protocols and acceptance criteria for proof loading of reinforced concrete bridges, beam experiments were analysed. In these experiments, different loading speeds, constant load level times, numbers of loading cycles, and required number of load levels were evaluated. The result of these experiments is the development of a standard loading protocol for the proof loading of reinforced concrete bridges. Based on these limited test results, recommendations for acceptance criteria are also proposed.

Keywords: acceptance criteria; beam test; bending; load test; loading protocol; proof loading; reinforced concrete slab; shear; slab bridge.

INTRODUCTION

In the Netherlands, a large number of reinforced concrete bridges that were built in the decades following the second World War are reaching the end of their originally devised service life (Lantsoght et al., 2013). These bridges were designed for lower live loads than the currently governing live loads (CEN, 2003) and were designed according to codes that allowed higher shear capacities than according to the current provisions from Eurocode 2 (CEN, 2005). The result is that the shear capacity of 600 reinforced concrete slab bridges is subject to discussion in the Netherlands. To systematically rate these bridges, an assessment procedure following different Levels of Approximation is developed (Lantsoght et al., (in press)), called Levels of Assessment (LoA), based on slab shear experiments . Lower Levels of Assessment are less time-consuming, but give a more conservative assessment. If a bridge rates too low at LoA I, the calculation can be refined with the next LoA. Proof loading is used as the last resource, LoA IV. In a proof load test, a load is applied that results in the same sectional shear as the live load model. If the bridge can carry the applied proof load without showing signs of irreversible damage, it is experimentally demonstrated that the bridge is suitable for carrying the loads prescribed in the code. This paper deals with the development of a loading protocol and acceptance criteria for reinforced concrete bridges that need to be verified in shear and in bending moment. The acceptance criteria are used during the test to evaluate if further loading is allowed. This approach deviates from load testing of buildings, where the measurement results are evaluated after the test to see if the structural behavior is acceptable. If the acceptance criteria are exceeded, there is a chance that further increasing of the load will result in irreversible damage in the bridge.

RESEARCH SIGNIFICANCE

The novelty of the presented work is that acceptance criteria and a loading protocol are developed that are suitable for reinforced concrete bridges subjected to a proof load test. The development of the acceptance criteria is based on carefully executed experiments on reinforced concrete beams without shear reinforcement. For the first time, a distinction between acceptance criteria for bending moment and shear is made.

LOAD TESTING AND ACCEPTANCE CRITERIA

Load testing

Two types of load tests can be distinguished: diagnostic load tests and proof load tests. The goal of diagnostic load tests (Fu et al., 1997; Olaszek et al., 2014; Russo et al., 2000; Sanayei et al., 2016) is to improve analytical models of a structure based on measurements taken during a load test. A diagnostic load test is carried out at relatively low load levels. A proof load test (Aguilar et al., 2015; Casas and Gómez, 2013; Faber et al., 2000; Saraf et al., 1996) uses load levels that correspond to the factored live loads, and is used to directly evaluate a structure.

A number of codes and guidelines exist for load testing of structures. ACI 437.2M-13 (ACI Committee 437, 2013) and the German guidelines (Deutscher Ausschuss für Stahlbeton, 2000) deal with load testing of existing buildings. The Irish (NRA, 2014), British (The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges, 1998) and French (Cochet et al., 2004) guidelines describe diagnostic load tests on bridges. An NCHRP (NCHRP, 1998) report describes both diagnostic and proof load tests on bridges, but does not determine a loading protocol, required load, and acceptance criteria for proof load tests.

In the Netherlands, a number of proof load tests have been carried out over the last decade in order to establish guidelines for the proof load testing of reinforced concrete bridges. In particular, bridges with ASR-damage were studied, such as the viaduct Heidijk (Dieteren and den Uijl, 2009), the viaduct Vlijmen-Oost (Koekkoek et al., 2015b) and the viaduct Zijlweg (Koekkoek et al., 2015a). Additionally, a posted bridge, the viaduct De Beek (Koekkoek et al., 2016), a bridge that rated insufficiently for bending moment, the Halvemaans Bridge (Fennis and Hordijk, 2014), and a bridge with corrosion damage the viaduct Medemblik (Kapphahn, 2009), were proof load tested. The Ruytenschildt Bridge (Lantsoght et al., 2016a) was tested to failure.

Acceptance criteria from ACI 437.2M-13

ACI 437.2M-13 (ACI Committee 437, 2013) prescribes procedures and acceptance criteria for load testing of concrete structures (prestressed and reinforced concrete, with a maximum concrete compressive strength of 55 MPa = 8000 psi). The code describes a monotonic (Fig. 1a) and cyclic loading protocol (Fig. 1b). In the monotonic loading protocol, each load step should be held for at least 2 minutes, and the full test load should be applied for 24 hours. At least 24 hours after removing the load, a final set of response measurements should be taken. For the cyclic loading protocol, three load levels should be studied, with two cycles per load level (Casadei et al., 2005; De Luca et al., 2014; Galati et al., 2008; Ziehl et al., 2008). The first two cycles study the serviceability conditions, and the last two cycles study the full test load.

The first acceptance criterion is that the structure should show no evidence of failure. When deflections exceed precalculated deflections, when cracking is observed, or when cracks indicating anchorage problems appear, the licensed design professional should decide if the test can be continued. At signs indicating that shear failure is imminent, the structure is considered as having failed the load test. For monotonic loading, the measured deflection after the test (i.e. the residual deflection) is limited to:

$$\Delta_r \leq \frac{\Delta_l}{4} \tag{1}$$

$$\Delta_l \leq \frac{l_t}{180} \tag{2}$$

For a cyclic loading protocol, the first acceptance criterion is the deviation from linearity index, I_{DL}, with the angles as shown in Fig. 2a:

$$I_{DL} = 1 - \frac{\tan(\alpha_i)}{\tan(\alpha_{ref})} \leq 0.25 \tag{3}$$

The second acceptance criterion, see Fig. 2b, the permanency ratio I_{pr}, is defined as:

$$I_{pr} = \frac{I_{p(i+1)}}{I_{pi}} \leq 0.5 \tag{4}$$

where I_{pi} and $I_{p(i+1)}$ are the permanency indexes calculated for the *i*-th and (*i*+1)-th load cycles:

$$I_{pi} = \frac{\Delta_r^i}{\Delta_{\max}^i} \tag{5}$$

$$I_{p(i+1)} = \frac{\Delta_r^{(i+1)}}{\Delta_{\max}^{(i+1)}} \tag{6}$$

The third acceptance criterion requires that the residual deflection, Δ_r, measured at least 24 hours after removal of the load, fulfils Eq. (1).

Acceptance criteria from the German guidelines

The German guideline for load testing (Deutscher Ausschuss für Stahlbeton, 2000), originally developed for concrete buildings, is suitable for plain and reinforced concrete. Testing of shear-critical structures or structures that could exhibit a brittle failure mode is not allowed. A cyclic loading protocol of three load levels with at least one cycle per level is prescribed. Five acceptance criteria are defined in the German guideline. The first criterion is a limiting concrete strain:

$$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0} \tag{7}$$

The measured strain ε_c should be smaller than the limiting strain $\varepsilon_{c,lim}$ (0.6 ‰, or 0.8 ‰ if the compressive strength is larger than 25 MPa = 3626 psi) minus the strain ε_{c0} due to the permanent loads. In practice, ε_{c0} is taken from the linear finite element model that is used to prepare for a proof load test, and thus uses the assumption of linear elastic material behavior. The second criterion is a limiting strain in the steel:

$$\varepsilon_{s2} < 0.7 \frac{f_{ym}}{E_s} - \varepsilon_{s02} \tag{8}$$

This criterion becomes the following when the stress-strain relation of the steel is fully known:

$$\varepsilon_{s2} < 0.9 \frac{f_{0.01m}}{E_s} - \varepsilon_{s02} \tag{9}$$

The third criterion is based on the crack width w and the increase in crack width, Δw, as given in Table 1. The fourth acceptance criterion is that no non-linear behavior can occur, typically evaluated on the load-deflection graph, or if more than 10% permanent deformation is found after removing the load. The fifth criterion limits the strains in the shear span of beams without shear reinforcement to 60% of the strains from Eq. (7) for the strain in the concrete compressive strut and to 50% of the strains from Eqs. (8) or (9) for the strain in the shear reinforcement. A test also needs to be stopped when the measurements indicate critical changes in the structure, when the stability of the structure is endangered, and when critical displacements occur at the supports.

EXPERIMENTS

Test setup and instrumentation

Two beams are tested specifically to study the acceptance criteria, and two additional experiments from earlier testing at Delft University of Technology (Yang et al., 2016) were added to complete the analysis. The beams are simply supported and subjected to a single concentrated load at a distance a from the support. A sketch of the test setup is shown in Fig. 3a for beam P804 and in Fig. 3b for beam P502. The width of the support and loading plates was 100 mm (4 in.).

The instrumentation on the beam consists of LVDTs, laser distance finders and acoustic emission sensors, see Fig. 3c. An overview of the functions of all applied sensors is given in Table 2.

Specimens and materials

The cross section of beam P804 is 800 mm × 300 mm (31.5 in × 11.8 in) and of beam P502 the cross section is 500 mm × 300 mm (19.7 in × 11.8 in). Glacial river aggregates with a maximum diameter of 16 mm (0.63 in) are used. The density of the concrete is 2429.6 kg/m^3 (152 lb/ft^3), which gives a load of 23.8 kN/m^3 (0.152 kip/ft^3). The measured values of the concrete compressive strength at 28 days is given in Table 3.

In P804, 6 plain reinforcement bars of soft steel with ϕ = 20 mm (0.78 in) are used. In P502, 3 plain reinforcement bars with ϕ = 20 mm (0.78 in) are used. This reinforcement is similar to the reinforcement (plain bars, relatively low yield strength) that can be found in existing reinforced concrete bridges. The measured yield strength of the steel is f_{ym} = 296.8 MPa (43047 psi) and the measured tensile strength of the steel is f_{um} = 425.9 MPa (61771 psi).

In Table 3, the predicted maximum load to cause a bending moment failure is given as P_{moment} and the predicted maximum load to cause a shear failure is given as P_{shear}. The determination of the maximum loads takes the selfweight of the beam into account, and uses the full static scheme of the test setup. For P_{shear}, the expression from NEN-EN 1992-1-1:2005 was used (CEN, 2005), with $C_{Rd,c}/\gamma_c$ = 0.15 for average values (König and Fischer, 1995). The expected maximum load (the minimum of P_{moment} and P_{shear}) is then highlighted in grey in Table 3.

Loading procedure

The loading protocol for experiments P804A1 and P804A2 was determined to study acceptance criteria and come up with recommendations for bridges. P804B and P502A2 are analyzed for acceptance criteria, but were testing using a faster loading protocol.

First, the typical ratio of the applied proof load to the maximum load to cause failure has to be estimated, to know which load levels in the beam tests will correspond to the loads in the field. The results of viaduct Zijlweg are analyzed for this purpose (Koekkoek et al., 2015a). The failure load is estimated with the Extended Strip Model, which leads to good predictions for the capacity of reinforced concrete slab bridges (Lantsoght et al., 2016c). This analysis showed that the load level that corresponds to the proof load is 46% of the estimated failure load (Lantsoght et al., 2016b). As the depth of the field tests and the beams tested in the laboratory is similar, no influence of the size effect is expected.

According to ACI 437.2M-13 (ACI Committee 437, 2013), at least 3 load levels should be used. Instead of using two load cycles per load step, as shown in Fig. 1, 1 + 3 cycles are carried out: in the first cycle, small steps are used to go to the load level, and then three cycles are carried out without intermediate steps. In the first cycle, steps of 2 kN (0.45 kip) are used, and then the measurements are checked to verify if no indication of nonlinearity or onset of damage can be observed. After every cycle of the three regular cycles, the measurements are also checked for nonlinearity or indications of the onset of damage. A baseline load level higher than 0 kN is used, to make sure all measurements remain activated.

In P804A1, the influence of the loading speed is studied. At a low load level, four different loading speeds were used. The standard loading speed was determined based on the loading speed used for viaduct De Beek (Koekkoek et al., 2016). In the test, the loading speed was constant at 5.4 kN/s (1.21 kip/s) for the first test location and 7.3 kN/s (1.64 kip/s) for the second test location. A loading speed of 5 kN/s (1.12 kip/s) is taken as a reference speed for the laboratory tests. Since the loading is displacement-controlled, the applied loading speed used in the laboratory is 0.2 mm/s (0.008 in/s). Additionally, the loading speeds 0.004 mm/s (0.00016 in/s), 0.04 mm/s (0.0016 in/s) and 0.4 mm/s (0.016 in/s) are tested. The full loading protocol, as executed during the test, is shown in Fig. 4a and contains 42 load cycles and 8 load levels.

In P804A2, the influence of keeping the load constant was studied. The 1 + 3 cycles loading protocol was used starting at the second load level, but in the first cycle, the maximum load was kept constant for 15 minutes, see Fig. 4b. In total, 17 load cycles and 5 load levels are tested. In P804B (Fig. 4c), no cyclic loading was used; and in P502A2 (Fig. 4d), a cyclic loading protocol with less cycles was used. In P804B, 11 load levels were used; and in P502A2, 8 load steps at 5 load levels were used.

RESULTS AND DISCUSSION

Test results

In P804A1, the first cracks developed prior to the first load level of 75 kN (17 kip). At higher load levels, more flexural cracks developed until yielding of the reinforcement caused a flexural failure at 207 kN (47 kip), see Fig. 5a. In P804A2, lengthening of the existing cracks from P804A1 occurred. A brittle shear failure occurred at 232 kN (52 kip), see Fig. 5b. P804B was tested on the side of beam P804 that had no existing flexural cracks. A shear failure occurred at 196 kN (44 kip), see Fig. 5c. P502A2 had existing flexural cracks, and failed in flexure at 150 kN (34 kip), see Fig. 5d. The load-displacement diagram of all tests is given in Fig. 6. The values of the failure loads P_u and observed failure modes (flexure “F” or shear “S”) are given in Table 3. It can be seen that the failure modes were generally predicted correctly. The four experiments are used to analyze four cases: shear and flexural failures, both for previously cracked and uncracked beams.

Loading speed

In P804A1, the loading speed is varied: loading speeds of 0.004 mm/s (0.00016 in/s), 0.04 mm/s (0.0016 in/s), 0.02 mm/s (0.008 in/s) and 0.4 mm/s (0.016 in/s) are used. First, the effect of the loading speed on the increase in residual deformation is studied. If the time-dependent behavior of concrete plays an important role, it is expected that for slow loading speeds, the increase in residual deformation will be relatively larger. The increase in residual deformations is calculated as:

$$res_i = \Delta_{r,0,i} - \Delta_{r,0,(i-1)} \tag{10}$$

No relation between res_i and the loading speed could be found. Additionally, the relation between Δ_r and the loading speed is shown in Fig. 7a. The first point in this figure has a higher value, because in the first load cycle, the cracking moment was exceeded in the beam, which influenced the stiffness. The results shown no statistically relevant relation between Δ_r and the loading speed.

Next, the relation between the reduction in stiffness (comparing cycles i and i-1) and the loading speed is studied. For slower loading speeds, a larger reduction in the stiffness is expected. The stiffness of the unloading branch is analyzed, as it is less influenced by crack formation. It can be concluded, see Fig. 7b, that the effect of the loading speed on the stiffness reduction is irrelevant for the speeds used in field testing. Additionally, the influence of the loading speed on the strain rate and the energy in the cycle was found to be insignificant (Lantsoght et al., 2016b).

Number of loading cycles

The influence of the number of loading cycles in P804A1 was studied at the 75 kN load level (16.9 kip) by using 8 loading at a speed of 0.2 mm/s (0.008 in/s) and 3 cycles at the other tested speeds. The results are studied as a function of the energy in the cycle and in the loading branch of the cycle, see Fig. 7c. It can be seen that the results stabilize in the 4th cycle, which supports the proposal for a loading protocol of 1 + 3 cycles for higher load levels, and three cycles for lower load levels.

Constant load

In P804A1 and P804A2, the period of time used for constant loading and between load cycles was evaluated. In P804A1, cycles 30 (30 minutes constant load and rest), 34 and 38 (15 minutes load and rest) have longer constant loading and rest periods. In P804A2, during the first load cycle of each load level the load was applied for 15 minutes, followed by a rest period of 15 minutes, see Fig. 4. From the test results of P804A1, it seems that after a longer loading period, the stiffness is larger. In other words, a longer loading period seems to create some recuperation in the beam. In P804A2, the reduction of the stiffness during the experiment was very small, because the beam was fully cracked by P804A1. No effect of the constant loading periods is observed on the energy in the cycles, nor on the residual deformations. When looking at the results of the measured strains, a decrease in strain between the beginning and end of a loading cycle can be observed. However, because the experiment is executed in a displacement-controlled way, this observation is related to the effect that the applied load is reduced when the applied deformation is kept constant.

Analysis of acceptance criteria from the German guidelines

First, the criteria from the German guidelines (Deutscher Ausschuss für Stahlbeton, 2000) are evaluated. The acceptance criterion related to the steel strain, Eqs. (8) and (9), is not evaluated because this criterion requires the removal of the concrete cover, which is not always allowed by the bridge owner. The first evaluated acceptance criterion is related to the concrete strain, Eq. (7), and the results of this analysis are given in Table 4, indicating the load at which the criterion is exceeded, $P_{\varepsilon max}$. The loads range from 44% to 62% of the failure load. This acceptance criterion can thus be used in practice.

The second evaluated acceptance criterion is related to the crack width, see Table 1, and the results of this analysis are given in Table 4. P804B was not tested in a cyclic way, and in P502A2 crack widths were not measured, so that only the results of P804A1 and P804A2 are analyzed. P804A1 is a test on a beam with no existing cracks, so the requirements for new cracks from Table 1 can be evaluated. P804A2 has existing cracks, so the requirements for existing cracks from Table 1 are governing. During P804A1, the criterion is exceeded at LVDT12 in the second load cycle – a result that would be too conservative for practice: further loading did not yet lead to irreversible damage or failure. However, it must be noted that the absolute values of the measured crack widths are extremely small. Therefore, it is proposed to omit all crack widths smaller than 0.05 mm (0.002 in) for the analysis – these results are reported in Table 4. In P804A2, the criterion for the maximum increase in crack width is exceeded at LVDT15 in load step 9. It can thus be concluded that this acceptance criterion can be applied, provided that crack widths smaller than 0.05 mm (0.002 in) are neglected.

A last criterion that is evaluated is the residual deflection. The requirement that the residual deflection Δ_r should not be more than 10% of the maximum deflection in a load cycle Δ_{max} is evaluated. Since a baseline load level is used in the experiments, the residual deflection does not correspond to a case with a load of 0 kN (0 kip). Therefore, the stiffness of the unloading branch is used to find the residual deflection that would correspond to a load of 0 kN (0 kip), Δ_r^*, as sketched in Fig. 2b. The results are given in Table 4. In P804A1, the requirement is exceeded in the first load cycle. In P804A2, the requirement is exceeded in the first load cycle if Δ_r is used, and after failure if Δ_r^* is used. In P502A2, unloading to 0 kN (0 kip) was used, so that $\Delta_r = \Delta_r^*$. The results in Table 4 indicate that the acceptance criterion based on the residual deflection is not generally applicable.

Analysis of acceptance criteria from ACI 437.2M-13

The deviation from linearity index I_{DL}, see Fig. 2a, is a function of the loading scheme. In P804A1, the deviation from linearity index I_{DL} is exceeded in the 10th load cycle, one of the cycles to 75 kN (16.9 kip). In P804A2, I_{DL} was not exceeded in any load cycle. The deviation from linearity index I_{DL} can only be used with the cyclic loading protocol described in ACI 437.2M-13 (ACI Committee 437, 2013), see Fig. 1b, which cannot directly be used for bridges.

Similarly, it is found that the permanency ratio I_{PR} as an acceptance criterion can only be used together with the cyclic loading protocol from Fig. 1b, in which fixed values for the minimum and maximum loads need to be used (for example, by applying the loads in a load-controlled manner). If a manually operated system with hydraulic jacks is used in the field, reaching the exact same load over several load cycles becomes difficult. If the value of the residual deformation in the i+1-th cycle is smaller than in the i-th cycle, or if the maximum deformation in the i+1-th cycle is smaller than in the i-th cycle, I_{PR} becomes negative, which disturbs the results.

Finally, the criterion for the residual deflections can be evaluated. In ACI 437.2M-13 (ACI Committee 437, 2013), the limit to the residual deflection is 25% of the maximum deflection. These limiting values are given in Table 4 as $\Delta_{lim,ACI}$. In P804A1, this criterion was exceeded in every step, and in P804A2 only in the loading cycle to failure. In P502A2, the criterion is never exceeded. Again, it is concluded that a criterion based on residual deflections is not recommended.

RECOMMENDATIONS FOR BRIDGE APPLICATIONS

Proposed loading procedure

A cyclic loading protocol is recommended for load testing of bridges. Contrarily to ACI 437.2M-13 (ACI Committee 437, 2013), four load levels, and four cycles per load level are recommended. Of these four load cycles, the first cycle will be used to gradually go to the maximum load in the cycle, then keep the load constant until stabilization of the measurements, and then unload to the baseline load level. The baseline load level is necessary to keep all instrumentation activated. Then, three cycles without intermediate steps to the maximum load of that load level are carried out. The four recommended load levels are:

1. A low load level, to check proper functioning of all sensors;
2. The serviceability limit state load level;
3. An intermediate load level;
4. The maximum load level for which the bridge should be rated through the proof load test.

For the low load levels (up to the serviceability limit state level), three load cycles are sufficient, and the first slow load cycle can be omitted. An example of a loading procedure is shown in Fig. 8.

Even though the number of tested beams is limited, the number of cycles studied in these experiments is sufficient to support the presented recommendations. As such, further research to define the loading protocol is not urgently needed.

Proposed acceptance criteria

When analyzing the experimental results, the difference between acceptance criteria for shear and flexure, and between previously cracked in bending and uncracked conditions becomes clear. An overview of the recommended acceptance criteria for these resulting four cases is given in Table 5. The concrete strain criterion, Eq. (7) from the German guideline (Deutscher Ausschuss für Stahlbeton, 2000) is recommended. The requirements for w_{max} and w_{res} from Table 1 are simplified and crack widths of smaller than 0.05 mm (0.002 in) are neglected.

The deviation from linearity index I_{DL} depends on the loading protocol, see Fig. 2a. A simplification of this acceptance criterion uses the stiffness reduction, based on the stiffness as the tangent in the load-displacement graph. An overview of these results is given in Table 4. For P804A1, the first loading step had a low stiffness as the result of the occurrence of the first crack, so that the second loading cycle is used instead. In P804B, small steps were used to increase the load, which makes it difficult to find the stiffness from the load-displacement diagram. For the case of a test for flexure, with no previous bending cracks, a stiffness reduction of ≤ 25% can be used as an acceptance criterion, whereas for the other cases, a stricter limit of 5% can be recommended.

The deformation profiles in the longitudinal and transverse direction, as well as the load-displacement diagram should be evaluated in real time during the load test. The stiffness criterion is closely related to the load-displacement diagram. An example of the deformation profiles from P804A1 is given in Fig. 9. For the horizontal deformations, it can be seen that the shape of the profile changes at 120 kN (27.0 kip). For the vertical deformations, a similar observation can be made at 160 kN (36.0 kip). The results of the four experiments, considering the horizontal and vertical deformation profiles, are presented in Table 4. In P804A2, the vertical deformation plot did not signal distress prior to failure, but in all other cases both the horizontal and vertical deformation plot showed changes well in advance of failure. The analysis of these plots is thus recommended as an acceptance criterion.

These proposed acceptance criteria for bridge load tests are based on the presented preliminary study, which was limited to four experiments. Further experiments, especially on beams failing in shear, can be recommended to fine-tune and optimize the proposed acceptance criteria.

SUMMARY AND CONCLUSIONS

Proof load testing is considered the last method for rating of reinforced concrete bridges before strengthening or replacement is recommended. The current codes and guidelines mostly deal with either diagnostic load testing for bridges or proof load testing of buildings. Guidelines for proof load testing of bridges, indicating the required measurements and interpretation thereof, are necessary, especially because of the risks involved with the high load levels necessary in proof load tests.

This paper focuses on the development of acceptance criteria and a loading protocol for proof load testing of concrete bridges. Heavily instrumented reinforced concrete beams were tested in flexure and shear to evaluate of the acceptance criteria from the German guidelines and ACI 437.2M-13. Several parameters that influence the loading protocol were studied in depth, and a recommended loading protocol for bridge proof load tests was developed. For the acceptance criteria, all load cycles of each test need to be evaluated. Therefore, the proposed acceptance criteria can be considered as a preliminary result, based on exploratory testing, which needs further experimental verification in the future. The proposed acceptance criteria are based on the existing acceptance criteria, but have been adjusted for practical considerations related to bridge proof load testing.

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NOTATION

a = distance between the center of the load and the center of the support

a_v = distance between the face of the load and the face of the support

d = effective depth

$f_{0.01m}$ = average yield strength based on a strain of 0.01% (elastic zone)

$f_{c,cyl,m}$ = average cylinder concrete compressive strength

f_{ym} = measured yield strength of steel

f_{um} = measured tensile strength of steel

lim = criterion that is limiting

l_t = span length

res_i = the increase in the residual deformation between loading cycles (i-1) and i

s_{laser} = deflection as measured by the laser distance finders at the position of the load

$\tan(\alpha_i)$ = the secant stiffness at any point i on the increasing loading portion of the load-deflection envelope

tan(α_{ref}) = the slope of the reference secant line for the load-deflection envelope

w = crack width for a new crack

w_{lim} = limiting crack width, calculated based on w_{max}

w_{max} = crack width at maximum load of a given load cycle for a new crack, or increase in crack width at the maximum load for an existing crack

w_{res} = residual crack width at unloading of a given load cycle

$C_{Rd,c}$ = calibration factor from Eurocode shear expression, = 0.18

E_s = modulus of elasticity of reinforcement steel

F = flexural failure

F = measured load

FM = failure mode

I_{DL} = deviation from linearity index

I_{Pi} = permanency index at the i-th load cycle

$I_{P(i+1)}$ = permanency index at the (i+1)-th load cycle

I_{PR} = permanency ratio

Level = percentage of maximum load at which an acceptance criterion is exceeded

LS = load step

P = load

P_{def} = load in experiment at which the deformation profiles change

P_{EI} = load in experiment at which stiffness criterion is exceeded

P_{min} = baseline load level

P_{max} = maximum load in a given load cycle

P_{moment} = calculated load at which a bending moment failure takes place

P_{shear} = calculated load at which a shear failure takes place

P_u = load at failure of the specimen

P_w = load in experiment at which crack width criterion is exceeded

$P_{\varepsilon max}$ = load in experiment at which strain criterion is exceeded

P_{Δ} = load in experiment at which residual deflection criterion is exceeded

Red_{EI} = reduction in the stiffness with regard to the first load cycle

S = shear failure

γ_c = material factor for concrete, = 1.5

ε_c = strain measured during proof loading

$\varepsilon_{c,lim}$ = limit value of the concrete strain : 0.6 ‰, and for ≥ B25 this can be increased up to maximum 0.8 ‰

ε_{c0} = 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

ε_{s2} = steel strain during experiment: directly measured or derived from other measurements

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

ρ_l = ratio of longitudinal reinforcement

Δ = deflection

Δ_l = maximum deflection

$\Delta_{lim,DAfStB}$ = limit to residual deflection given in the German guideline

$\Delta_{lim,ACI}$ = limit to residual deflection given in ACI 437.2M-13 (ACI Committee 437, 2013)

Δ_{max} = maximum deflection of a load cycle

Δ^1_{max} = maximum deflection during load cycle 1

Δ^2_{max} = maximum deflection during load cycle 2

Δ^i_{max} = maximum deflection during load cycle *i*

Δ^{i+1}_{max} = maximum deflection during load cycle i+1

Δ_r = residual deflection

Δ_r^* = residual deflection recalculated at a load of 0 kN (0 kip)

$\Delta_{r,i}^*$ = residual deflection recalculated at a load of 0 kN (0 kip) in the *i*th loading cycle

Δ^1_r = residual deflection after load cycle 1

Δ^2_r = residual deflection after load cycle 2

Δ^i_r = residual deflection after load cycle i

Δ^{i+1}_r = residual deflection after load cycle i+1

Δw = increase in crack width for an existing crack

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TABLES AND FIGURES

List of Tables

Table 1 - Requirements for crack width for newly developing cracks *w* and increase in crack width *Δw* for existing cracks.

	During proof loading	After proof loading
Existing cracks	$\Delta w \leq 0.3$ mm = 0.01 in	$\leq 0.2\Delta w$
New cracks	$w \leq 0.5$ mm = 0.02 in	$\leq 0.3w$

Table 2 – Overview of applied sensors

nr	purpose
LVDT1	horizontal deformation
LVDT2	horizontal deformation
LVDT3	horizontal deformation
LVDT4	horizontal deformation
LVDT5	horizontal deformation
LVDT6	horizontal deformation
LVDT7	horizontal deformation
LVDT8	horizontal deformation
LVDT9	vertical deformation
LVDT10	vertical deformation
LVDT11	vertical deformation
LVDT12	crack width
LVDT13	crack width
LVDT14	strain over 1 m
LVDT15	crack width
LVDT16	crack width

Laser01	deflection at support
Laser02	deflection under load
Laser03	deflection at support
Laser04	deflection under load

Table 3 – Properties of specimens. Conversion: 1 MPa = 0.145 ksi; 1 kN = 0.22 kip; 1 mm = 0.04 in.

Test	a (mm)	d (mm)	a/d	a_v/d	ρ_l	$f_{c,cyl,m}$ (MPa)	P_{shear} (kN)	P_{moment} (kN)	P_u (kN)	FM
P804A1	3000	755	3.97	3.84	0.83	63.51	273	199	207	F
P804A2	2500	755	3.31	3.18	0.83	63.51	219	248	232	S
P804B	2500	755	3.31	3.18	0.83	63.51	219	248	196	S
P502A2	1000	465	2.15	1.94	0.68	71.47	150	154	150	F

Table 4 – Evaluation of existing and proposed acceptance criteria. Conversion: 1 kN = 0.22 kip, 1 mm = 0.04 in.

Strain criterion from German guideline				
Test	ε_{c0} (με)	$\varepsilon_{c,lim} - \varepsilon_{c0}$ (με)	$P_{\varepsilon max}$ (kN)	Level (%)
P804A1	36	764	91	44
P804A2	33	767	120	52
P804B	33	767	111	57
P502A2	22	778	93	62

Crack width criterion from German guideline								
Test	LS	w_{max} (mm)	w_{res} (mm)	w_{lim} (mm)	lim	LVDT	P_w (kN)	Level (%)
P804A1	30	0.2441 0.0021	0.0760 0.0640	0.0732 0.0006	w_{lim}	LVDT15 LVDT16	140	68
P804A1	38	0.5569	0.2156	0.1671	w_{max}	LVDT15	180	87
P804A1	2	0.0024	0.0284	0.0007	w_{lim}	LVDT12	75	36
P804A2	9	0.3141	0.0144	0.0628	w_{max}	LVDT15	160	69

Residual deformation criterion from German guideline and ACI 437.2M-13								
Test	LS	Δ_{max} (mm)	Δ_r (mm)	Δ_r^* (mm)	$\Delta_{lim,DAfStB}$ (mm)	$\Delta_{lim,ACI}$ (mm)	P_Δ (kN)	Level (%)
P804A1	1	2.509	1.001	0.727	0.251	0.627	75	36
P804A2	1	3.172	0.416	-0.082	0.317	0.793	75	32
P804A2	17	12.973	11.348	11.239	1.297	3.243	230	100
P502A2	7	5.262	0.311	0.311	0.526	1.315	150	100

Proposed stiffness criterion				
Test	LS	Red_{EI} (%)	P_{EI} (kN)	Level (%)

P804A1	25	24.67	95	46
P804A1	26	51.79	120	58
P804A2	5	6.37	115	50
P804A2	17	15.14	230	100
P804B	4	25.77	110	56
P502A2	2	21.72	75	50
Proposed criterion from deformation profiles				
	Horizontal deformations		Vertical deformations	
Test	P_{def} (kN)	Level (%)	P_{def} (kN)	Level (%)
P804A1	120	58	160	77
P804A2	200	87	-	-
P804B	110	56	110	56
P502A2	125	83	125	83

Table 5 – Overview of proposed acceptance criteria for reinforced concrete bridges.

Conversion: 1 mm = 0.04 in.

	Previously cracked in bending moment or not?	
Failure mechanism	*Uncracked*	*Cracked*
Flexural failure	Concrete strains (Eq. (7)) $w_{max} \leq 0.5$ mm $w_{res} \leq 0.1$ mm Stiffness reduction ≤ 25 % Deformation profiles Load-displacement graph	Concrete strains (Eq. (7)) $w_{max} \leq 0.5$ mm $w_{res} \leq 0.1$ mm Stiffness reduction ≤ 5 % Deformation profiles Load-displacement graph
Shear failure	Concrete strains (Eq. (7)) $w_{max} \leq 0.3$ mm Stiffness reduction ≤ 5 % Deformation profiles Load-displacement graph	Concrete strains (Eq. (7)) Stiffness reduction ≤ 5 % Deformation profiles Load-displacement graph

List of Figures

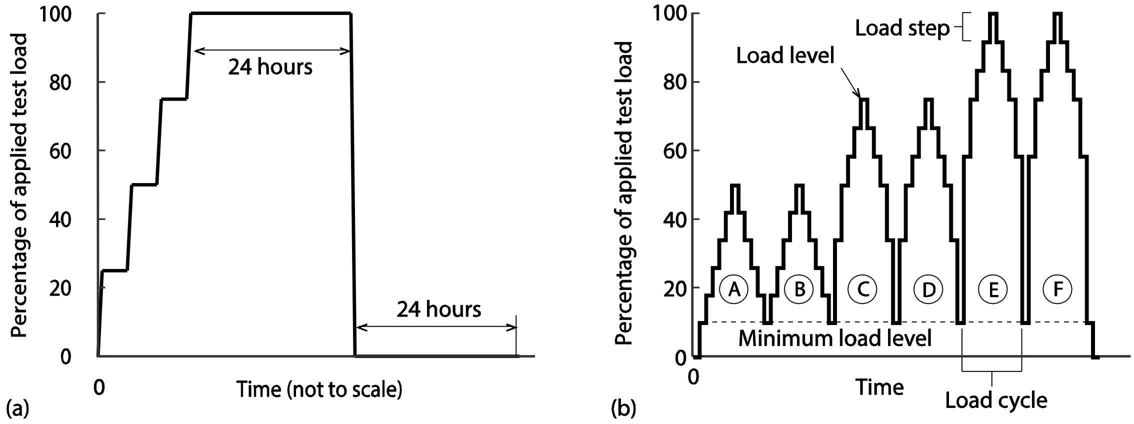

Fig. 1–Loading protocols from ACI 437.2M-13 (ACI Committee 437, 2013): (a) monotonic loading protocol; (b) cyclic loading protocol

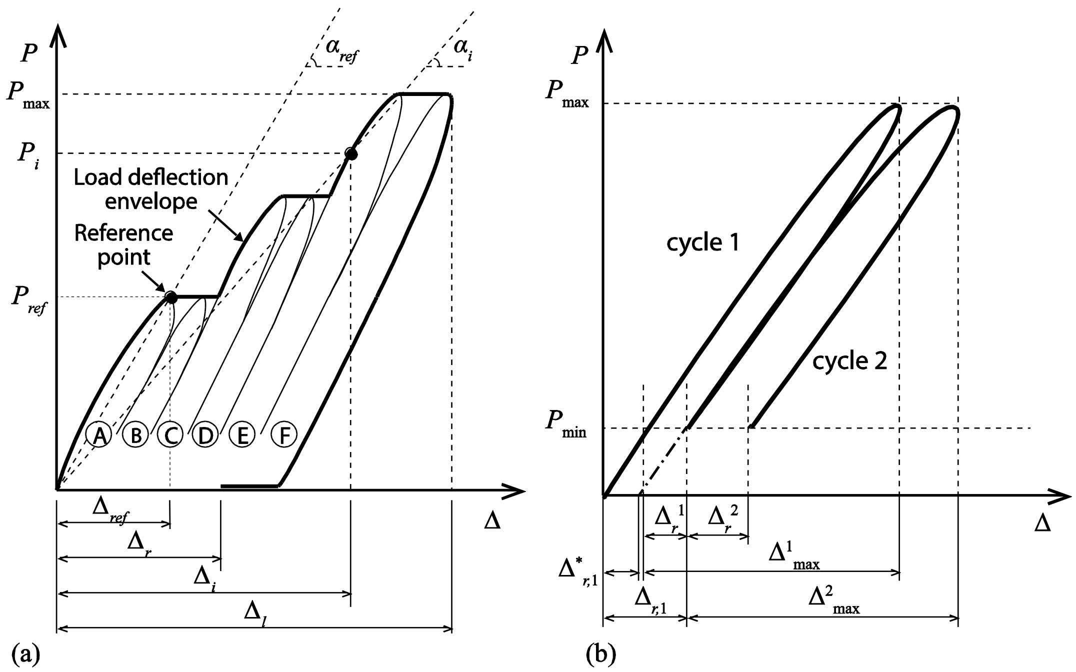

Fig. 2– Definitions used for the acceptance criteria from ACI 437.2M-13 (ACI Committee 437, 2013): (a) Deviation from Linearity, I_{DL}; (b) Permanency Ratio, I_{PR}, also showing residual deflection after a cycle $\Delta_{r,1}$ and the calculated value using the stiffness of the unloading branch to zero load, $\Delta_{r,1}^*$.

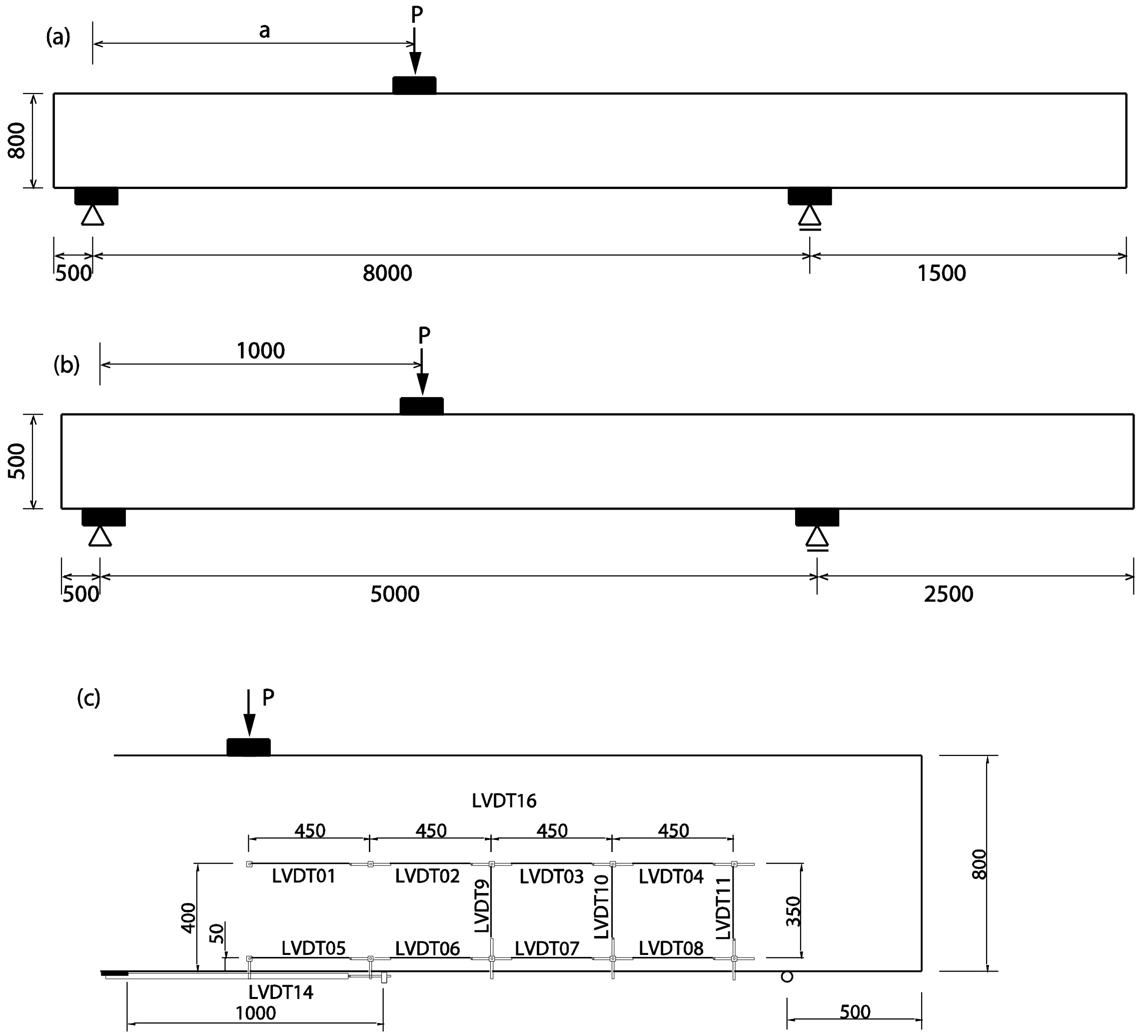

Fig. 3– (a) Test setup and geometry of P804A1, P804A2 and P804B; (b) Test setup and geometry for P502A2; (c) instrumentation on P804A1. Conversion: 1 mm = 0.04 in.

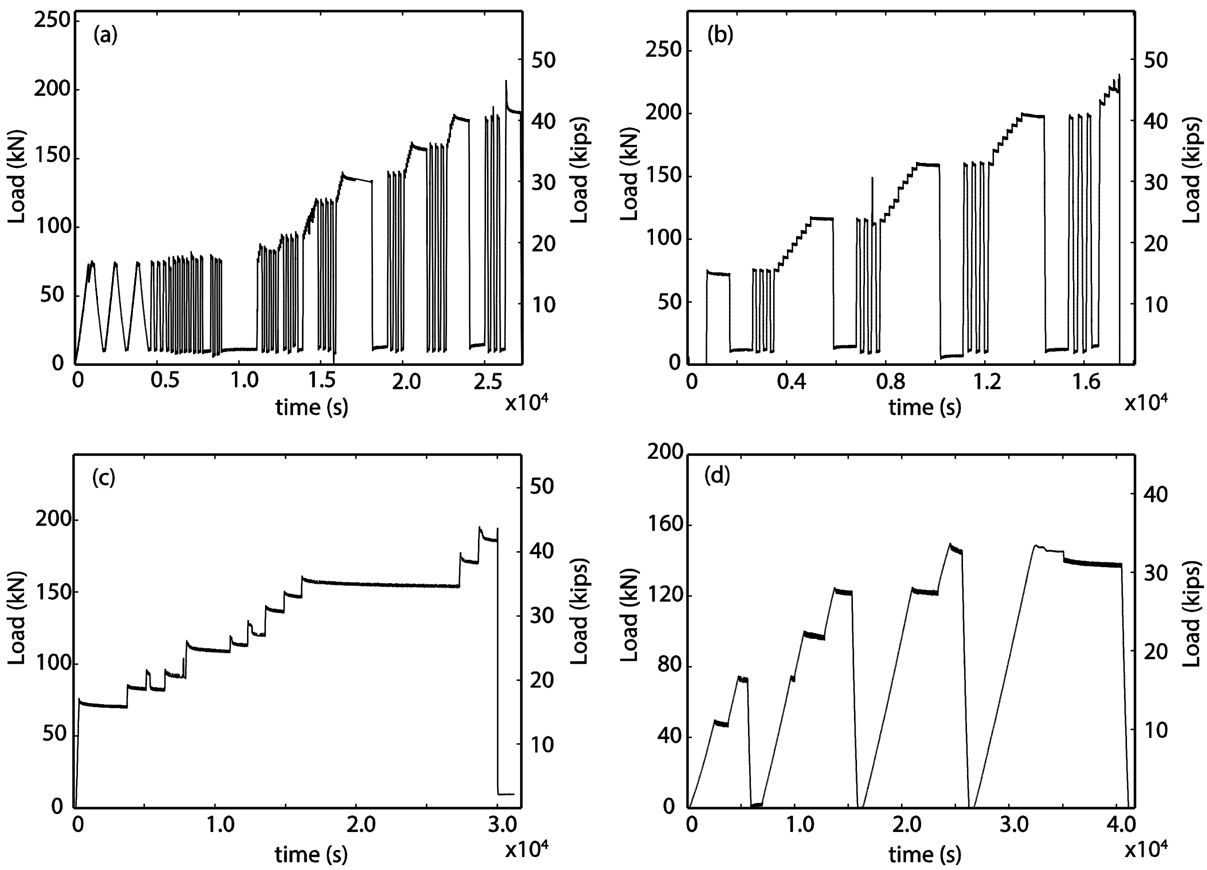

Fig. 4-Loading scheme of: (a) P804A1, (b) P804A2, (c) P804B, (d) P502A2.

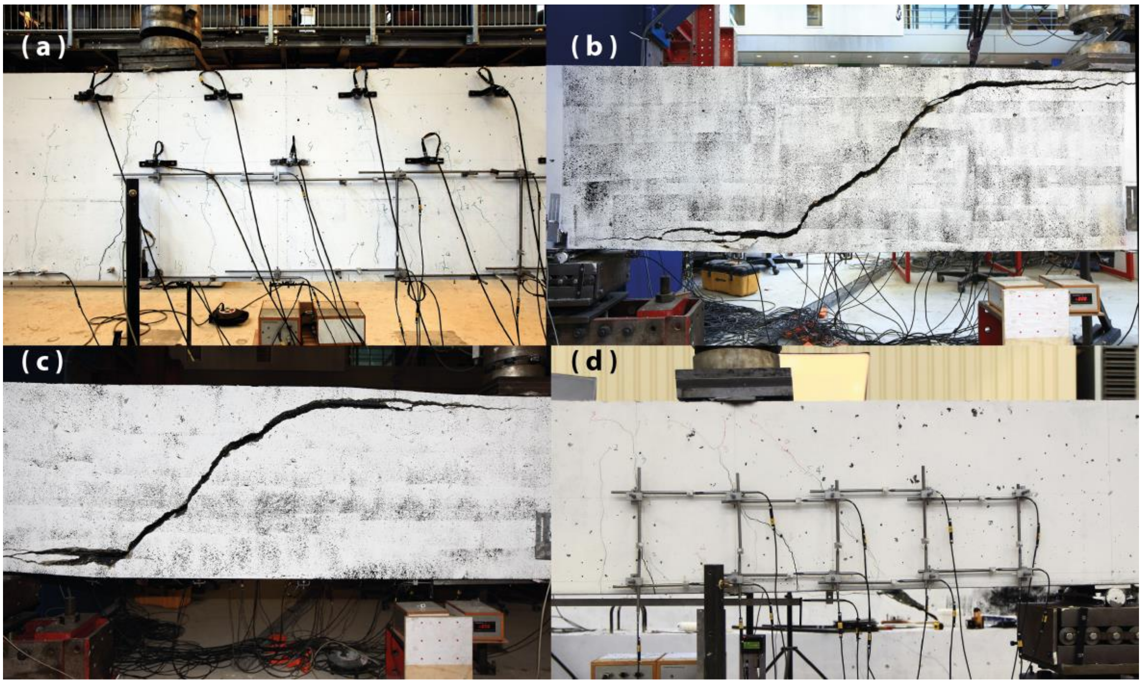

Fig. 5 – Observed failure modes: (a) P804A1; (b) P804A2; (c) P804B; (d) P502A2.

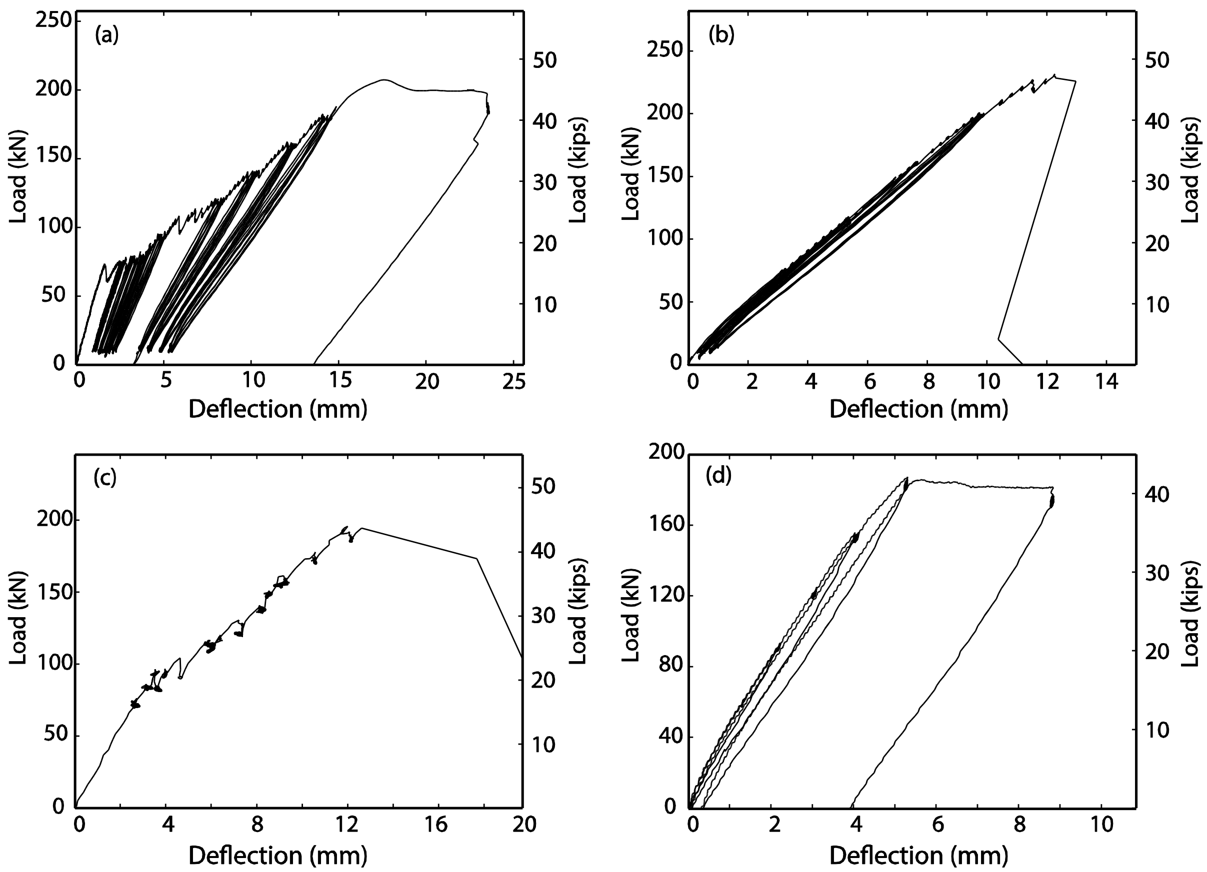

Fig. 6 – Measured load-displacement diagrams: (a) P804A1; (b) P804A2; (c) P804B; (d) P502A2. Conversion: 1 mm = 0.04 in.

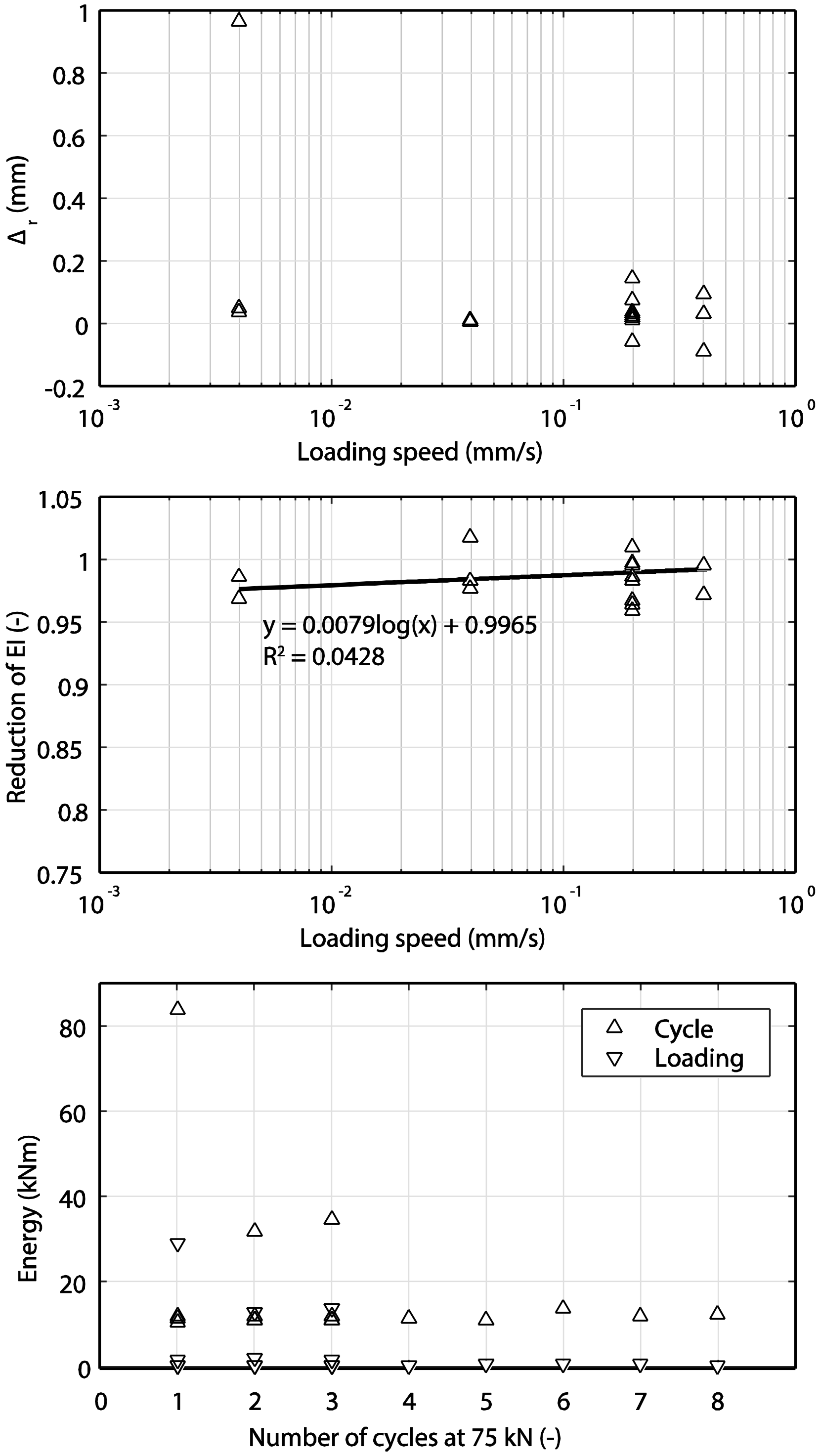

Fig. 7 – Evaluation of P804A1 for loading protocol: (a) Relation between residual deflection Δ_r and the loading speed; (b) Relation between stiffness reduction and loading speed; (c) Influence of number of cycles on energy in cycle or energy in loading branch of cycle. Conversion: 1 mm = 0.04 in, 1 kNm = 0.7 kip-ft.

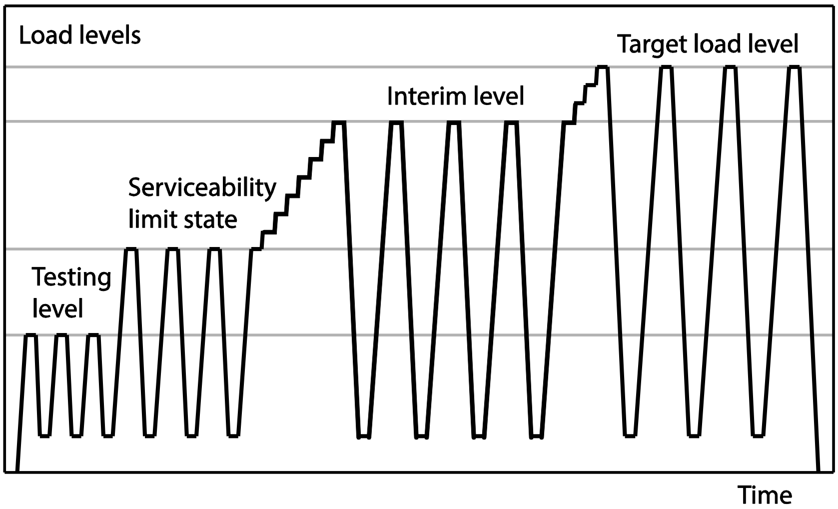

Fig. 8 – Example of the proposed loading protocol. Conversion: 1 kN = 0.22 kip.

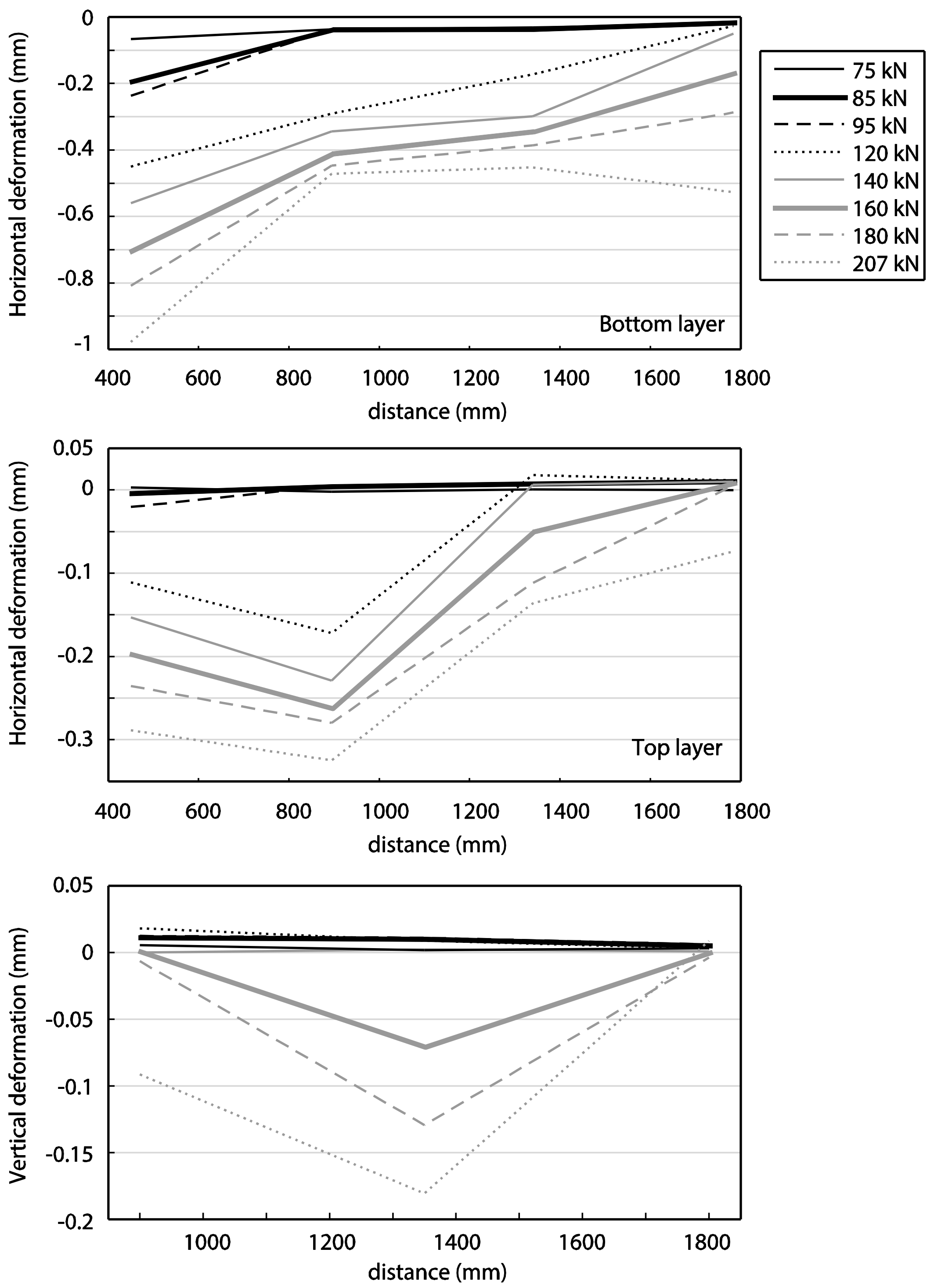

Fig. 9 – Deformation plots: (a) upper layer of horizontal deformations; (b) lower layer of horizontal deformations; (c) vertical deformations. Conversion: 1 mm = 0.04 in.