Validation of proof loading methods: With a basis in collapse testing and stop criteria crack evaluation

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Abstract

Safe proof loading of concrete bridges requires reliable stop criteria. Such criteria must ensure sufficient margin to the ultimate resistance and may be based on observations from advanced testing. In particular, the identification of thresholds related to pre-stressed and non-shear-reinforced slab structures is currently ongoing with an addition of specific focus on potentially brittle failure modes of such structures. This paper presents representative examples of identifying stop criteria and target load thresholds using a combination of laboratory- and in-situ testing. Responses from recently tested structures and structural elements will be presented to enable discussion and perspectivation. The presented test results show measurable warning with sufficient margin from crack initiation to stop criterion. It was additionally seen that the target load often may be the governing threshold when proof load testing.

Keywords: Proof load testing; stop criteria; response margins; shear-critical bridges,

1 Introduction

Response evaluation of existing concrete bridges through load testing has been a topic of increasing interest during the last decade. Such evaluations have been performed using diagnostic loading, proof loading or loading to failure. The increased interest originates from the pressing need to extend the service life of bridges but also from an increased demand dedicated to continuously increasing load from heavy transport vehicles. Research related to collapse testing often shows a higher capacity than obtained from applied theories [1–3]. Reasons for such discrepancies can often be attributed to uncertainties regarding the structure, its materials, or its structural interaction between bridge elements. Such uncertainties may also relate to: 1) boundary conditions and their actual effect, 2) stress redistribution, 3) conservative theoretical assumptions, 4) additional load paths and load-carrying mechanisms. It seems difficult to separate these into unique contributions, but the sum of contributions may have a major effect on the structural resistance.

It is seen from the literature that loading methods have varied significantly with different related scopes [4]. In an ongoing Danish bridge testing project, a specific focus is on applying loading representative to the actual vehicles that drive the road network [5,6], whereas in the Netherlands, the focus is on aligning with the Eurocode live load model.

For proof load testing purposes, stop criteria need to be identified to ensure that a proof load test can be terminated in due time before permanent damage or collapse. Evaluation of the margin from the detection of the stop criteria to the failure level is one of the important objectives in a proof loading perspective [7]. Such evaluations may often need to be supported by measurements to provide robustness in the proof loading assessment.

The present paper provides a status update on recent developments within the field of proof loading. Based on laboratory and field collapse test results from Denmark and the Netherlands, the margin associated with crack evaluation is indicated for non-shear reinforced OT-slabs and solid slabs. Several methods for crack evaluation are considered and the overall findings provide the basis for validation of proof loading methods, as demonstrated in multiple proof loading pilot projects. The addressed research questions are:

- Is it possible to monitor crack initiation with a sufficient margin to the applied stop criterion, even for prestressed and non-shear reinforced slabs?
- Which monitoring equipment can be used as a support to crack measurements?
- Is it possible to apply sufficient in-situ monitoring to evaluate the stop criterion and are they practical in a field testing scenario?

2 Stop criterion thresholds

Only limited recommendations for stop criteria are given in the literature. Consequently, stop criteria have been a topic of interest in recent studies. Typical suggestions for stop criteria may be divided into qualitative and quantitative thresholds:

- Qualitative stop criteria which evaluate deformation profiles, load/deflection diagrams, crack initiation and cracking patterns, and overall structural behavior. And they require engineering judgement for their evaluation.
- Quantitative stop criteria are typically measured strain, crack width, stiffness reduction, or other unique measurable parameters.

Cracks in concrete may be observed as both qualitative and quantitative criteria, first as crack identification and subsequently for crack width monitoring. The German guideline [8] offers stop criteria for crack widths in buildings, $w_{max} \leq 0.5$ mm for new cracks and $w_{max} \leq 0.3$ mm for existing cracks. A more recent theoretically based criteria for flexure-critical situations, based on Frosch's beam cracking theory [9], is proposed by [10]. In the presented research, the calculated values for crack widths vary from $w_{max} \leq 0.11$ mm to $w_{max} \leq 0.19$ mm. In addition, it is proposed that crack widths $w \leq 0.05$ mm should not be considered structural cracks. For service limit loads related to concrete members by EN 1992-1-1 [11] a maximum crack width of $w_{max} \leq 0.2$ mm is given for pre-stressed members with bonded tendons. However, caution has to be taken in the unique case since this threshold can be depended on the prestress level- and application. $w_{max} \leq 0.3$ mm for non-prestressed structures (for most exposure classes). For flexure-critical situations, with sufficient ductility, this approach of monitoring towards a threshold value using for instance digital image correlation (DIC) has been shown to work well and may be considered safe and robust [7]. However, it is still an open question whether this is also the case for non-shear reinforced slabs in which a brittle failure may occur. A first proposal for a set of stop criteria for non-shear-reinforced concrete slabs, based on shear theories (Critical Shear Crack Theory and Critical Shear Displacement Theory) is presented in [12].

When considering stop criteria, it is important to note that:

- A stop criterion must provide a sufficient margin, but should also not be overly conservative, as this would result in premature termination of the test and a lower capacity assessment [10].
- Multiple stop criteria thresholds are needed as a basis for proof loading
- It must be ensured in the preparations that the stop criteria can be monitored and evaluated throughout the in-situ proof loading procedure.

2.1 Margin observed in failure tests

The results in this section consider examples from predominantly laboratory slab testing performed in the Netherlands and Denmark, but also one local in-situ slab test performed in Denmark. Figure 1 shows the response from the testing of two scaled OT-slabs. An applied crack width threshold of 0.2 mm based on EC2 [11]. It is seen that the response of the OT slabs was ductile, and it was thus a flexure-critical test. Crack initiations measured by DIC were observed with a moderate margin between crack detection and the crack width criterion, but a significant margin to the ultimate capacity, see Table 1.

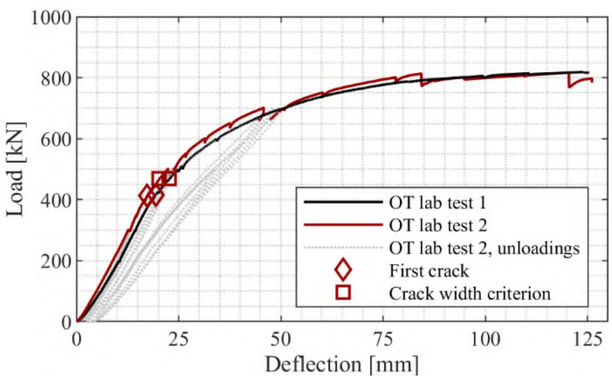

Figure 1. Response curves from scaled laboratory OT-slab tests (Denmark, 2020) [13–15].

Figure 2 shows test examples for the non-prestressed and non-shear reinforced slabs. In these tests, the crack width threshold was 0.3 mm based on EC2.

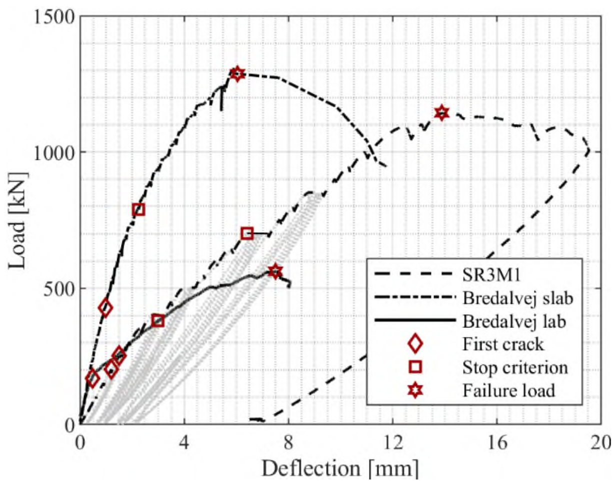

Figure 2. Load-deflection diagrams from experiment SR3M1 from TU Delft [16], Bredalvej bridge in-situ slab test (AAU, June 2024), Bredalvej bridge cutout (AAU, November 2024).

The tests were much less ductile and failed in a brittle manner, however considerable margins were still observed between the first identified crack, the crack width criterion and the failure load, see Table 1. Load levels (P) and associated deflection values (δ) are given at crack detection (P_{cr} , δ_{cr}) and crack width criterion (P_{st} , δ_{st}). Percentages (representing margins) are calculated as percentage of the ultimate load and of the ultimate deflection for load values (P_m) and deflection values (δ_m), respectively.

Table 1. Observed margins in laboratory and in-situ slab tests.

Test name	Crack detection				Crack width criterion			
	P_{cr} [kN]	$P_{m.cr}$ [%]	δ_{cr} [mm]	$\delta_{m.cr}$ [%]	P_{st} [kN]	$P_{m.st}$ [%]	δ_{st} [mm]	$\delta_{m.st}$ [%]
OT lab 1	415	**51**	19.4	**15**	468	**57**	22.7	**18**
OT lab 2	413	**50**	17.3	**14**	468	**57**	20.2	**16**
SR3M1	203	**18**	1.21	**9**	702	**61**	6.42	**46**
Bridge slab	429	**33**	0.97	**16**	789	**61**	2.26	**37**
Bridge cutout	169	**30**	0.49	**7**	380	**68**	3.38	**45**

2.2 Evaluation of results towards proof loading

The presented findings combined with additional in-situ tests and pilot projects are currently providing a good basis for the definition of stop criteria related to potentially brittle non-shear reinforced slabs. The results show that although the tests have reduced ductility, there is a significant margin. Since proof load tests are often performed with an incremental load-controlled loading, the interesting margin is the margin for the load, which is observed to be 18% to 61%, 33% to 61%, and 30% to 68% for the three non-shear reinforced slabs. Between crack detection and the crack width criterion, the crack width can be continuously evaluated. The load steps only need to be small enough for such evaluation to be efficient. In addition, it should be noted that these tests were designed to provide a shear failure. In a real proof loading situation, a representative loading from e.g. a standard vehicle from the Danish classification system [17] may provide more- and earlier bending cracks.

Another observation from the tests is that the maximum load levels are high. Consequently, in most of the cases, the target load seem to be the governing threshold. The target load may be estimated through reliability-based methods [5].

3 In-situ proof loading validation

Performing laboratory tests serve as an excellent basis for proof loading methods and regards to evaluation of monitoring methods towards stop criteria monitoring. Moreover, the knowledge gained in the laboratory can provide information in a Bayesian way for the evaluation of the reliability during a proof load test [18]. However, when performing actual proof load testing, a substantial number of parameters can affect the outcome of testing and there may be a significant difference between the real in-situ bridge structure compared to laboratory testing. Some of these aspects are:

- Short testing time and high safety requirement, limiting the application of sensors.
- Imitation of a real classification vehicle instead of a single concentrated load.
- Practical in-situ challenges (electrical outlets, tooling, etc.).
- Environmental conditions (light, moisture, temperature, etc.).
- Limited time for detailed adjustments and post-processing.
- Large structure and working above and below bridge with difficult or unsafe access, see Figure 3 and Figure 4.
- Several unknown parameters compared to very controlled laboratory testing.

Figure 3. Example of In-situ conditions, Denmark.

Figure 4. Example of access difficulties for applying instrumentation, the Netherlands (Vechtbrug).

3.1 Example from The Netherlands

An example of a proof load test from the Netherlands is the pilot test on the viaduct Zijlweg [19,20]. Upon assessment, the shear capacity of this viaduct was found to be insufficient; this as a result of large uncertainties on the shear capacity due to alkali-silica reaction present in the superstructure. Therefore, it was decided to carry out a proof load test on the first span of the bridge (which does not cross the highway, for safety reasons) at a flexure-critical and shear-critical location. Figure 5 shows the four-span reinforced concrete slab bridge. Figure 6 shows the loading protocol used during the proof load test for shear. The target proof load was determined as the load that would generate the same sectional shear as the factored load combination critical for assessment, magnified by at least 5% to take the uncertainties into account. A cyclic loading protocol was used to check repeatability of measurements and overall linearity.

Figure 5. Viaduct Zijlweg, The Netherlands.

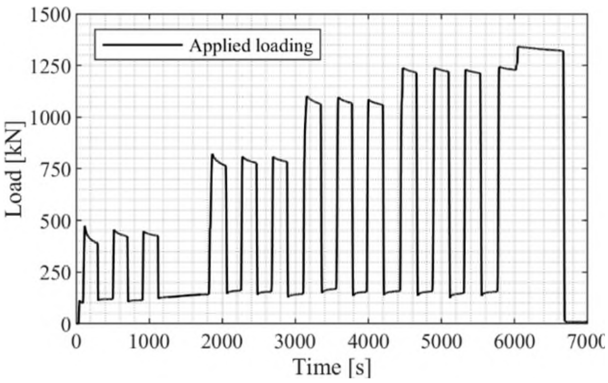

Figure 6. Measured loading procedure for shear proof load test on Viaduct Zijlweg.

Figure 7 shows the top view of the bridge during the proof load, indicating the position of the tandem. A wheel print of 230 mm × 300 mm was used, which is in line with a national guideline [21] from the Netherlands for fatigue in joints, and which is considered more conservative due to the smaller loading area than the 400 mm × 400 mm from the Eurocode Load Model 1 [22].

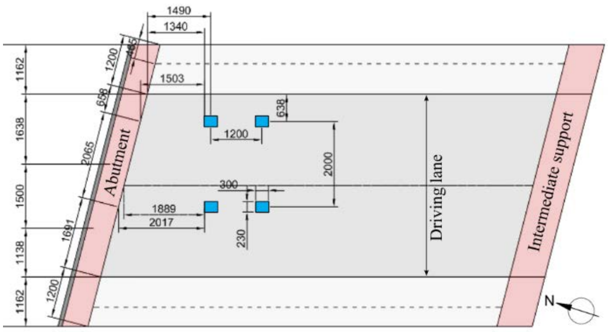

Figure 7. Position of wheel loads for shear proof load test.

Figure 8 shows the envelope of the load-displacement during the proof load test, indicating linear behavior for all load levels. The details of the crack width measurements (followed at three different locations) are included in Figure 9. As an alternative to DIC measurements, the crack widths were here measured using a setup with LVDT's. For all crack width measurements, the maximum measured value is well below the physical threshold for cracking of 0.05 mm. All cracking below this threshold can be considered microcracking without a structural significance. As such, the crack width limits, both for serviceability, as well as based on theoretical considerations, are not reached in this proof load test.

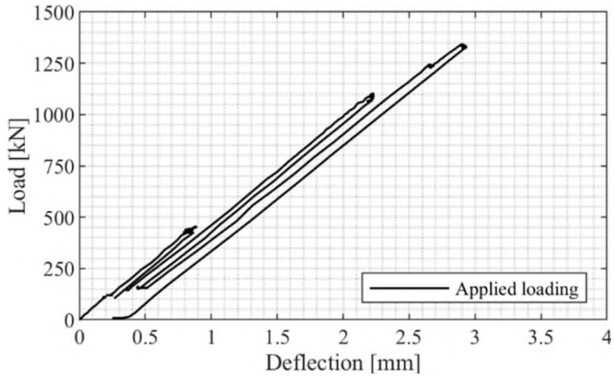

Figure 8. Envelope of the force-displacement diagram for the shear position on Viaduct Zijlweg.

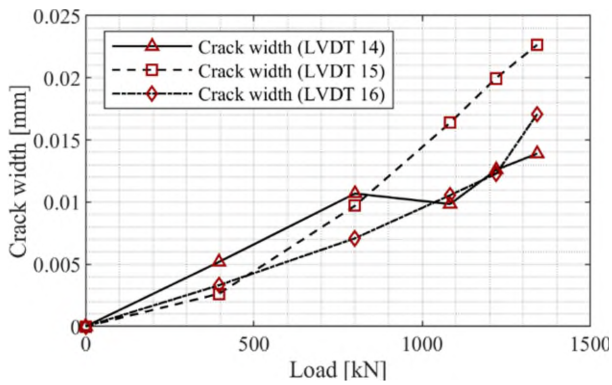

Figure 9. Increase in crack width during the shear proof load test.

3.2 Example from Denmark

In 2020, a pilot project was arranged with the aim to validate the approaches described in the Danish proof loading guideline [23]. It was important to ensure that the described proof loading method can be competitive compared to other service life extension methods. The objective was thus to upgrade a road stretch with four class 80 bridges between the two towns Assens and Nørre Aaby on

Funen in Denmark [5,24], see Table 2. A bridge class of 100 would enable the road stretch to being part of the Danish heavy transport network, and the four bridges were thus a limiting factor.

Table 2. Proof loaded bridges in pilot project [24].

Test day	Bridge No.	Bridge type	Class	Span [m]
1	3851	In-situ cast slab	80	2.1 m
2	3700	OT-slab	80	6.5 m
2	3699	In-situ cast slab	80	3.8 m
3	3720	In-situ cast slab	80	4.0 m

The Danish guideline can be used to upgrade bridges with a span from 2 – 12 m. Such bridges represent the majority of the Danish bridge mass and the four bridges were thus ideal for validation of the proof loading methods.

The bridges were tested over three days and loaded with advanced heavy transport vehicles utilizing hydraulic control of individual axles. These vehicles are shown in Figure 10. It is seen that the approach follows the Danish classification system where the stable vehicle B load is placed in the vicinity of the vehicle A which is the vehicle that decides the classification through the applied proof loading magnitude.

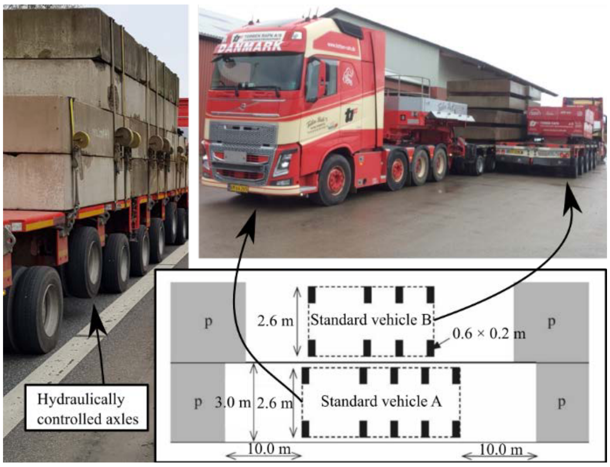

Figure 10. Example of heavy transport vehicles used for load application and simulating vehicles A and B of the Danish classification system.

The different spans necessitated the use of differentiated load positioning and number of axles. An example of the wheel loading is illustrated in Figure 11 using a two-axle configuration but three axles were also applied to some of the bridges on the road stretch [5]. The figure additionally shows how the supporting axles were placed outside the bridge span. Without moving the vehicle, the central loading axles could then be raised for zero loading as well at the beginning of the test. This way of testing is an efficient and time-effective method of loading which complies well with the demands of a proof load test.

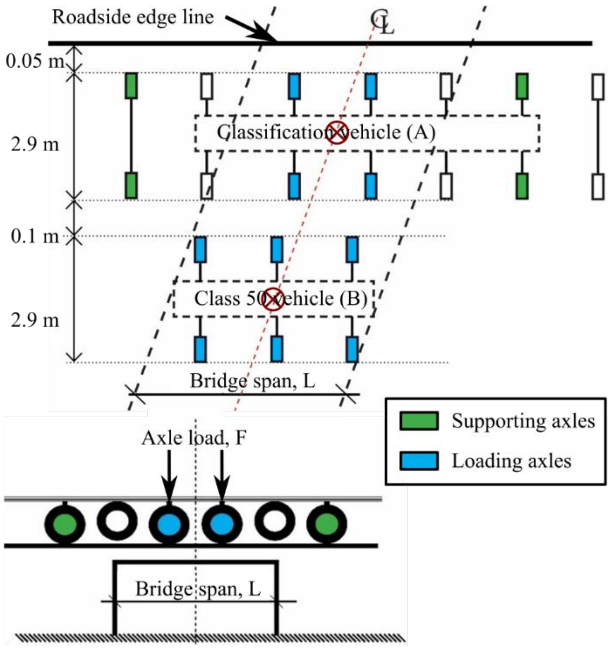

Figure 11. Example of axle placing using two primary axles for vehicle A.

To further comply with the desired measurable parameters described in the Danish guideline [23], a limited but specialized monitoring package was applied, see Figure 12. The package included:

- Loading output from the hydraulic station.
- Deflection measured by land surveyor. Both midspan deflection and abutment settlements were measured.
- The response curve was analyzed during testing, e.g. looking for stiffness change.
- Additional safety was ensured by using 2D DIC for crack detection and evaluation.

The load was applied in increments to allow continuous evaluation of the bridge response and monitoring information during testing.

To prepare for DIC, a surface pattern was applied to the concrete surfaces. Minimal artificial lighting (two LED lights in each test) was applied underneath the bridges to improve the DIC pattern recognition.

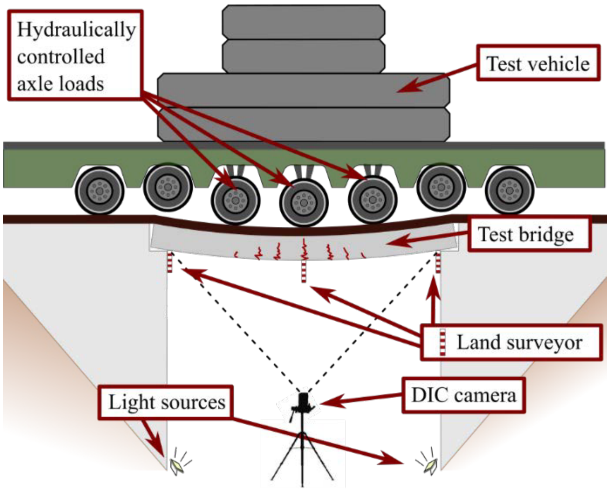

Figure 12. Monitoring setup used for proof loading.

The light sources were battery-powered and equipped with power banks for increased service time. A generator was brought on-site as backup power, but the full setup could run without power for multiple hours. In case of rain, a small tent was brought for the monitoring station. Such matters illustrate a selection of the challenges that must be solved when testing in-situ. For further information on the test setup and performed tests, see [5,24].

All four proof load tests successfully reached the designated target load. The maximum deflections were 0.45 mm, 2.0 mm, 0.63 mm, and 0.65 mm for the bridges, respectively. The response of bridges 3700 and 3720 are shown in Figure 14. No signs of distress were observed during the tests.

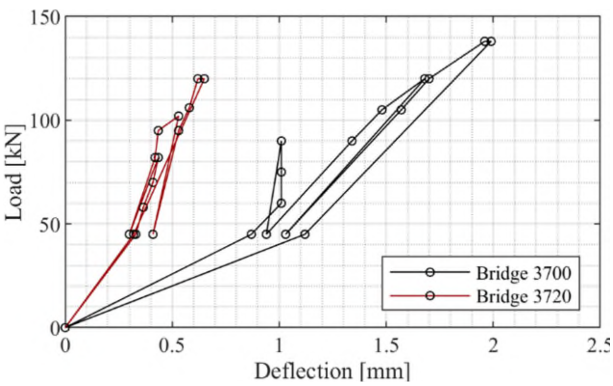

Figure 13. Response for bridges 3700 and 3720.

The optimized test methods provided an efficient, simplified approach that ensured the project remained on schedule and within its budget constraints. Since the target load was achieved without distress, the bridges were reclassified from class 80 to class 100. Consequently, the entire road stretch between Assens and Nørre Aaby could be upgraded for class 100 heavy transports.

The applied continuous DIC monitoring of the bridges' bottom surfaces confirmed that no cracking was present in any of the bridges. The full-field strain plot for Bridge 3700 at peak load (Figure 15 shows some imaging noise, likely due in-situ conditions. Despite this, the absence of cracking was clear, and previous tests and subsequent proof-load evaluations provide confidence in this observation. No control measurements were performed to verify the DIC results, however, the LVDT setup used by TU Delft could have been an option for such verification.

The pilot proof-load tests from the Netherlands and Denmark demonstrate that existing bridges can be evaluated and reclassified using the described proof loading methods. While none of the tested bridges were expected to be shear-critical under the applied loading, they could have been if a shear-critical load position had been utilized. However, shear-critical load applications are not representative of actual heavy transports. The applied loading reflects the true forces bridges in the road network experience. Importantly, no monitoring-based stop criteria were triggered, and the target load was the key threshold. Previous results indicate that even for shear-critical bridges, a sufficient margin would likely exist, and any signs of irreversible damage would have been detected by the monitoring.

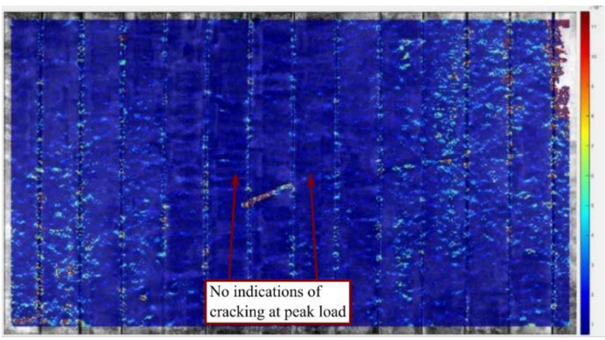

Figure 14. DIC-monitored surface of bridge 3700 at maximum load in the proof load test.

4 Conclusions

This study demonstrates that the presented proof-loading methods offer a robust framework for evaluating and reclassifying existing concrete slab bridges. Laboratory and in-situ tests showed sufficient margins between initial crack detection, crack width thresholds, and ultimate capacity. For the tested prestressed OT-slabs, ductile behavior was observed, whereas the non-shear reinforced slabs showed a more brittle failure mode yet maintained significant margins. Examples of proof load testing in The Netherlands and in Denmark have shown how a limited but specialized monitoring package can be sufficient to monitor for any indications of structural distress. The incremental load-controlled loading protocol allowed for timely evaluation of the measurements. No monitoring-based stop criteria was triggered, and all tests reached the target load and were thus up-classified. In the Danish tests, the applied loading was representative of actual Danish heavy transport classification vehicles and thereby more correctly reflecting the actual load effects on bridges. These findings throughout this paper indicate that the proposed stop criteria and applied monitoring methods can be used safely to upgrade bridges. Ultimately this contributed to extended service life and improved infrastructure resilience.

5 Acknowledgements

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