# In-situ and laboratory collapse testing in a proof loading perspective

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## Abstract

The field of proof-loading has expanded over the last decade with excellent examples of successful collaborations and multidisciplinary approaches. Advanced testing has, as one of the essential subjects in an interdisciplinary assessment, brought significant value to further understanding of structural responses and failure mechanisms related to concrete bridges. This paper presents laboratory and field collapse testing examples in the Netherlands and Denmark, and related investigations of the response of non-shear reinforced slabs until failure. A special focus is dedicated to load application, examples of test approaches, some practical insights and test result comparison. Considerations of the laboratory and field test planning in synergy will be discussed based on the results and experiences obtained. A substantial margin to ultimate failure was found from crack identification or other measurable warnings in all tests. These observations suggests that it is possible to get sufficient warning even for non-shear reinforced concrete slabs structures.

**Keywords:** collapse testing; field and laboratory testing; measurements; non-shear reinforced concrete slab; warning.

## 1 Introduction

In-situ load testing has a significant historical background as an evaluation method for the assessment of bridges. One of the earliest published examples is from 1913 when a flat arch bridge was loaded using a concentrated load at the centre of the arch [1]. One of the first in-situ tests using hydraulic jacks was performed in 1963 [2], where a three-span concrete bridge was loaded till collapse in a controlled manner. Many examples of bridge load testing have since been documented [3,4]. Often it seems complicated to compare the different load tests since they usually refer to unique bridge structures, test approaches, and research objectives [5]. The scopes of the load tests are also wide-ranging, including diagnostic testing, proof-load testing, and collapse testing. However, all projects seek to gather information concerning the bridges to verify and validate their unique structural response. Amongst the other load testing methods, collapse testing is the only testing method which can provide the ultimate capacity of a structure and various measurement of a structure evolute when the externally applied load increases. This information is valuable, especially for the development of proof load testing protocols. During proof loading, the safety of the structure is guaranteed by a set of stop criteria [6,7]. However, the residual capacity from the moment when stop criteria are reached to the ultimate capacity can only be observed through a collapse testing. Extensive research has been carried out over the last decade on proof loading of bridges and thus extend their service life [7,8]. However, reaching an internationally consistent way of proof loading concrete bridges remains challenging, because national historical aspects, laws, procedures, assessments, etc., can differ significantly. Nevertheless, experimental research outputs, both from in-situ collapse testing and laboratory testing, provide valuable outputs from an essential basis for research on the topic of proof load testing of bridges worldwide. Consequently, the present study presents examples of synergetic activities related to collapse testing and proof loading in an international collaboration between the Netherlands and Denmark.

### 1.1 Testing aims and hypothesis

In-situ testing as a practice can be more sophisticated than tests in laboratory conditions due to the environmental and size effects as well as traffic disturbances. This paper reflects on the mutual findings addressing the following research questions:

- Does the non-shear reinforced concrete slabs or beams collapse without warning, when testing?
- Can crack initiation be observed at a load level that has a significant margin to the load obtained at the ultimate capacity?
- Are the initial crack formations detected before permanent damage occurs?

## 2 In Situ Collapse testing

The possibility of testing a full bridge seldom arises. When it does, it is often in connection with bridges that are set for demolition. This was also the case in bridge testing projects conducted in the Netherlands and Denmark. Such projects present an opportunity to evaluate the structural response of an entire bridge or parts of a bridge. Preparation may consider environmental effects, bridge access demands, limitations to available test areas, short timeframe for testing, etc. Consequently, it often seems difficult to directly compare laboratory preparations with those of in-situ testing. Some of the main gains related to in-situ testing are: i) Assessment of the actual structural response, ii) In-situ monitoring validation, iii) Verification of applied test methodologies, iv) Real structure, real-time data acquisition, v) Load effect from representative load, vi) More exact input for multidisciplinary validation. Supporting tests in the laboratory may often be used to evaluate the in-situ observations further. In contrast, important gains related to laboratory testing may thus be: i) Detailed evaluation of failure initiations, ii) Further monitoring method calibration, iii) Evaluation of several identical specimens, iv) No in-situ preparation demands, v) Easier-to-use deformation-controlled loading

### 2.1 Loading

Since most load testing of bridges are related to bridge assessment, it is essential to mention that the design traffic load differs significantly between countries [9]. An example is the loading used in the Netherlands and Denmark.

In Denmark, administration and control are done using a unique classification system [10]. Both bridges and vehicles are classified using the load configurations based on this system. A vehicle is allowed to pass a bridge if the bridge class is higher than the vehicle class. Figure 1 illustrates how two vehicles are required when performing a classification. Standard vehicle B provides a stable load to the structure together with the evenly distributed load *P* and is adjacent to the standard vehicle A. The standard vehicle A load combined with all other loads provides the basis of the classification and must thus be within the bridge resistance limit.

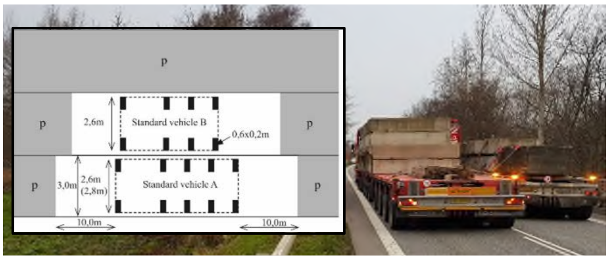


*Figure 1. Two adjacent standard vehicles [10,11].*

In the Netherlands, no vehicle classification system is used. Instead, the Eurocode 1 live load model (see Figure 2) is used as a basis to design the loading that needs to be applied during a proof load or collapse test [26]. The Eurocode 1 live load model consists of a design truck combined with a design lane load. The design truck has an axle load of $\alpha_{Q1}$ × 300kN in the first lane, $\alpha_{Q2}$ × 200kN in the second lane and $\alpha_{Q3}$ × 100kN in the third lane. All $\alpha_{Qi}$ equal 1. The lane load is applied over the full width of the lane and equals $\alpha_{qi}$ × 9kN/m$^2$ for the first lane and $\alpha_{qi}$ × 2.5kN/m$^2$ for all other lanes. In the Netherlands, for bridges with 3 or more notional lanes, the value of $\alpha_{q1}$ equals $\alpha_{q1}$ = 1.15 and for $i$ > 1 the value can be taken as $\alpha_{qi}$ = 1.4.

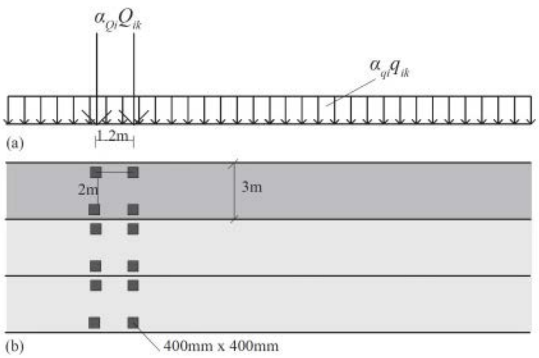


*Figure 2. Eurocode 1 live load model [12].*

Following the design principle of Eurocode load model, in a proof loading, a tandem load which can generate the same load effect of a target failure mode is applied.

## 2.2 Examples of In-situ testing

In the Netherlands, in-situ testing has been carried out with a main focus on a series of proof load tests [13], and in addition two noteworthy collapse tests have been carried out. The first collapse test was on a reinforced concrete slab bridge, the Ruytenschildt Bridge [4,14], and the second collapse test was on a post-tensioned slab-between-girder bridge, the Vecht Bridge [15].

For the testing of the Ruytenschildt Bridge in 2014, the main aim was to identify the risk of a shear failure, to validate instrumentation procedures, and to assess its ultimate capacity. For that reason, the load was applied using a single tandem system, see Figure 3.

*Figure 3. Load application Ruytenschildt bridge [4].*

For testing the Vecht Bridge in 2016, the main focus was on creating a concentrated load right above the post-tensioned girders, to study the difference in terms of shear behaviour between the girders in a bridge system and the isolated girders. Therefore, only one single concentrated load was applied on the tests on the Vecht Bridge, see Figure 4.

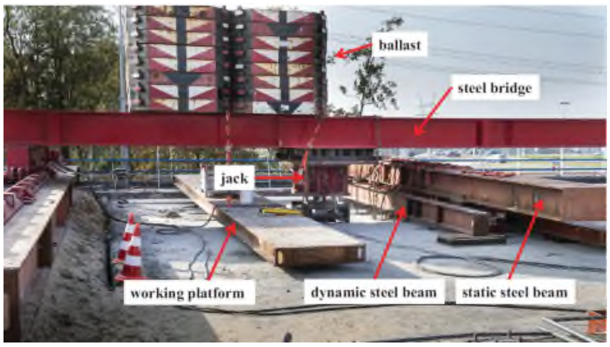


*Figure 4. Load application Vecht bridge [15].*

In the Danish research projects (2016-2026), standard vehicles from the Danish classification system have provided the basis for the applied loading, both in-situ and in the laboratories. In the early part of the project, OT-slabs (Overturned T-section beams, connected with in-situ cast concrete) were tested due to a concern that they would fail in a brittle manner without warning due to their limited or no shear reinforcement and lack of interaction between adjacent OT-beams. Figure 5 shows an example of the loading rig used to apply loading on the OT-slab bridges with a loading reflecting the representative Danish classification vehicles.

*Figure 5. Representative loading on OT-slab bridge (2016, Denmark) [5].*

Because the OT-slabs were found to have higher resistance than model predictions from in-situ test [5,16], an OT-slab bridge were cut into strips in the longitudinal direction; this to isolate specific areas and to initiate deformations and crack formations for monitoring detection. Loading was applied until the yielding regime to enable a full response evaluation, see Figure 6.

*Figure 6. Representative loading on the OT-strips (2016, Denmark) [5,17].*

As a step forward, in-situ research related to non-shear reinforced slabs (without prestressing) was carried out in Denmark. An example of more local in-situ loading of such slabs is depicted in Figure 7 from field tests in June 2024. The aim of testing was to investigate the full response, and the magnitude of warning and brittleness related to the failure development in such bridge type. The applied axle loads are shown in Figure 8. Only one axle load was applied to ensure shear failure. As seen from the test approaches of the Netherlands and Denmark, in-situ collapse testing was used to study the real structural effects. Findings used for test method updating and optimizations are typically applied in later in-situ proof loading pilot tests.


*Figure 7. Partial testing of bridge slab, (June 2024, Denmark) [18].*

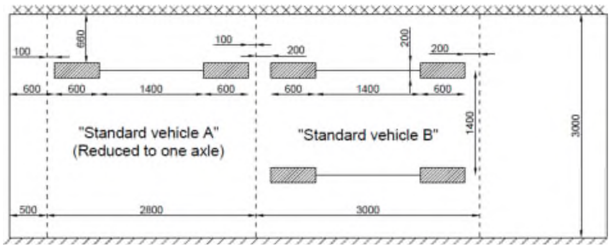


*Figure 8. Applied load according to the Danish classification vehicles, adjusted for shear failure.*

## 2.3 Laboratory testing at TU Delft

A substantial capacity was observed in the Ruytenschildt Bridge, but at the same time, a large number of bridges in the Netherlands are found to be insufficient for shear upon assessment. Consequently, there is an ongoing wish to use proof load testing to demonstrate that existing reinforced concrete slab bridges in the Netherlands has sufficient shear resistance concerning the requirement of heavier traffic load nowadays.

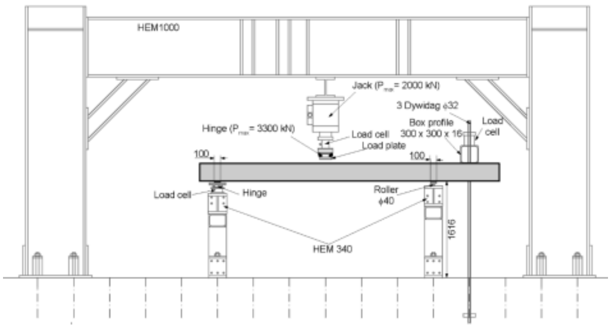


*Figure 9. Test setup of reinforced concrete slab experiments in the Netherlands.*

As part of this research, a series of experiments on straight and skewed slabs (5 m × 2.5 m × 0.3 m) were tested under cycles of loads (similar to the proof load testing protocol), see Figure 9 for the test setup. The tests were instrumented to identify precursors to shear failure.

## 2.4 Laboratory testing in Denmark

The high magnitude loading obtained in the in-situ tests of the Danish bridge testing project in 2016 was an eye-opener [5]. The capacity was extensively higher than expected, and consequently, significant redistribution was deemed to occur in the OT-slabs. Further investigations related to such slab types were thus performed in the DTU laboratory. Multiple 2/3 downscaled OT slabs were investigated to reveal interaction behaviour and potential stop criteria, see Figure 10 for the test setup.

*Figure 10. Scaled OT-slab tests in Denmark, [6].*

In addition, beam specimens from the in-situ slab test area (June 2024) are presently being tested in the Aalborg University laboratory.

# 3 Results and discussion

Load magnitudes, failure initiation, failure warning, and initial crack observations are necessary evaluations from a proof loading perspective. A comparison of results from the Netherlands and Denmark provides insight into the test-based findings. Evaluation of the load magnitudes from the two tests on OT-slab bridges were done using the described representative classification load. The results from the initial in-situ testing performed in 2016 is depicted in Figure 11. The first test obtained a maximum deflection of 21,7mm, corresponding to a loading magnitude of 456 tonnes. The second test reached a load of 473 tonnes with a related deflection of 9,1mm. A maximum axle load magnitude of 100 tonne was reached in both cases. No more load was available, and no visible cracks were seen when reaching the maximum applied load. Similarly, for the test of the Ruytenschildt Bridge, no failure occurred during the test of the first span when 300 tonnes of counterweight were used to apply the load. For the second span, additional load was ordered, and 400 tonnes of counterweight were applied to the structure, resulting in large settlements of the piers. The deflection of the slab at 400 tonnes was limited to 15 mm, see Figure 12.

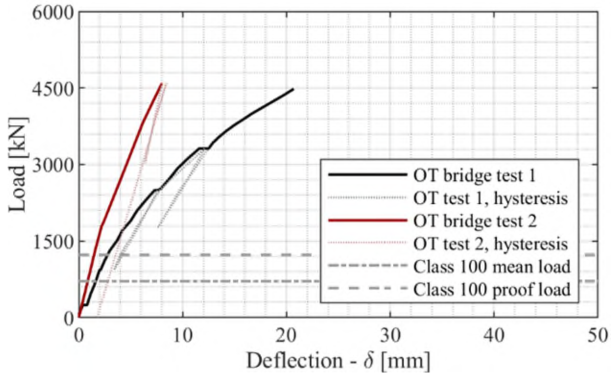


*Figure 11. High load magnitude testing of OT-slab bridges (2016, Denmark) [5].*

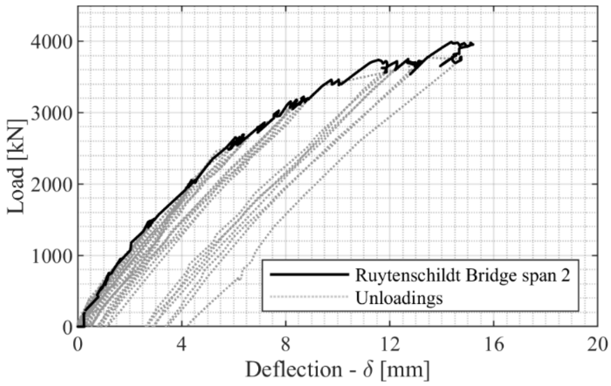


*Figure 12. Load-displacement diagram of span 2 of Ruytenschildt Bridge [14].*

From the in-situ strip tests in the Danish bridge testing project, it was seen that the expected yielding initiation was obtained, see Figure 13. In addition, cracks were detected somewhat at the yielding initiation, which is dedicated to the monitoring precision (conducted directly on the concrete surface). Even though the OT slab is a prestressing system, the initiation of the first crack was still observed with a distinguishable margin before the ultimate capacity of the structure, which was the yielding regime of the beam. Figure 14, shows the load-deflection curve related to the down-scaled OT-slabs tested in the DTU laboratory, subjected to a point load. It was seen from these tests that sufficient interaction between the OT-beams of the slab was reached. Consequently, full composite action was activated including yielding initiation. The first cracks detected by the optimized monitoring were seen at crack widths of approximately 0,1mm. Additionally noteworthy was that these tests had a point load area of 350x400mm with an of approximate applied load of 80 tonnes.

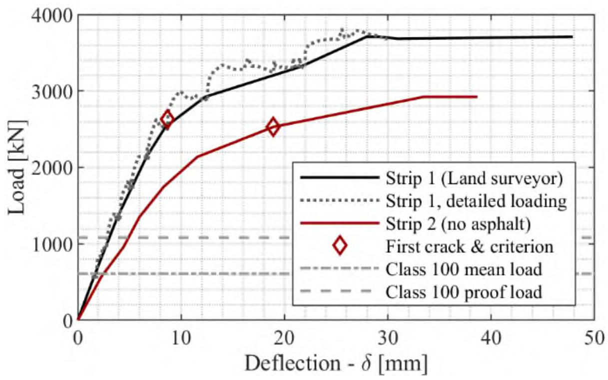


*Figure 13. Results from OT strip tests [17].*

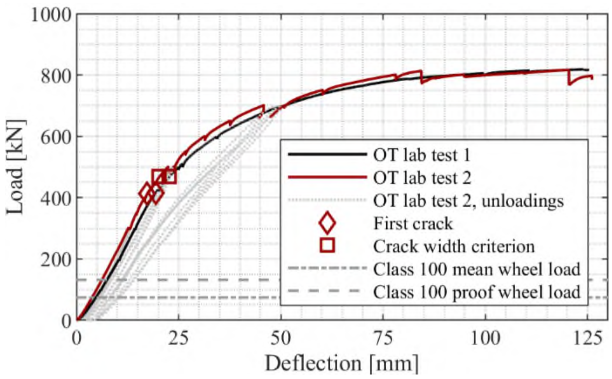


*Figure 14. Response curves from scaled laboratory OT-slab tests (2020, Denmark) [6].*

In the Netherlands, the tests of the Ruytenschildt bridge similarly showed a large residual capacity of reinforced concrete slabs, even when tested at the shear-critical location. In the load test, crack development was measured clearly before yielding of the reinforcement or the predicated shear capacity. As an additional remark, because of the geotechnical conditions the failure mode of the superstructure was dominated by bending with significantly higher capacity instead of a potential brittle shear failure. The experiments on the Vecht Bridge showed that the ultimate capacity of the system is high, and that this may result from additional load-carrying mechanisms such as compressive membrane action, compressive arching action, the diaphragms acting as intermediate supports and contributing to the compressive arching action, and load distribution between the girders, as well as redistribution after cracking. In the laboratory tests on the reinforced concrete slabs tested in the Netherlands, a focus was on deriving precursors for shear failure. For that purpose, the slabs were heavily instrumented, subjected to cycles of loads as used during a proof load test, and were carefully analysed. Figure 15 shows the response curve for the test of slab SR3M1, which failed in shear. It is seen that there is a significant margin from crack detection to actual failure.

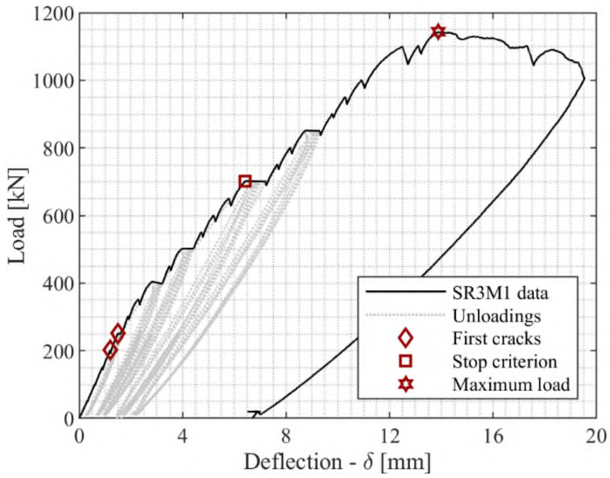


*Figure 15. Load-deflection diagram and observations of experiment SR3M1 [19].*

Similar evaluations were done in the non-shear reinforced slabs on the Danish bridge in June 2024, see Figure 16. In the test, the first cracks were detected with a significant margin to the predefined stop criterion and failure load. Even though shear failure were observed as shown in Figure 17.

*Figure 16. Shear failure in in-situ slab test (June 2024, Denmark).*

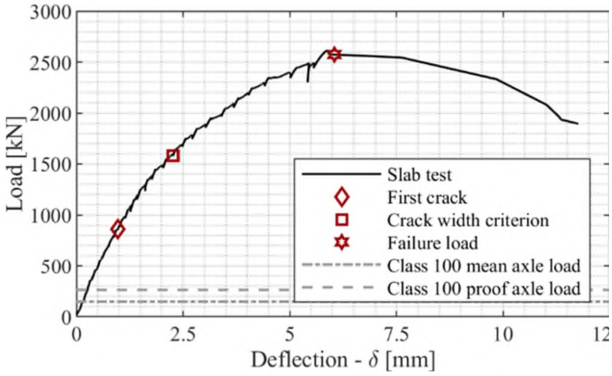


*Figure 17. Response curve from in-situ slab test (June 2024, Denmark).*

A representative response curve is given in Figure 18 for the ongoing tests of cut-out beam components. These results show similar observations with a large capacity margin between first crack, stop criterion and failure. Figure 19, shows an example of the obtained shear failure when testing the cut-out beam component from the in-situ test.

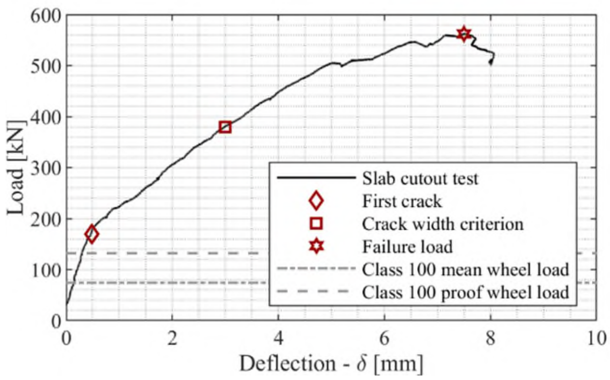


*Figure 18. Response curve from cut-out beam components (November 2024, Denmark).*

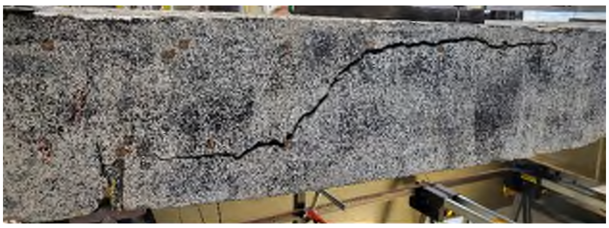

*Figure 19. Shear failure in beam cutout from June 2024 slab test (November 2024, Denmark).*

Figure 20 shows the DIC-processed failure pattern on the bottom surface of SR3M1. The shear crack opening could be captured by using differential displacement measurements from the top and bottom surfaces.

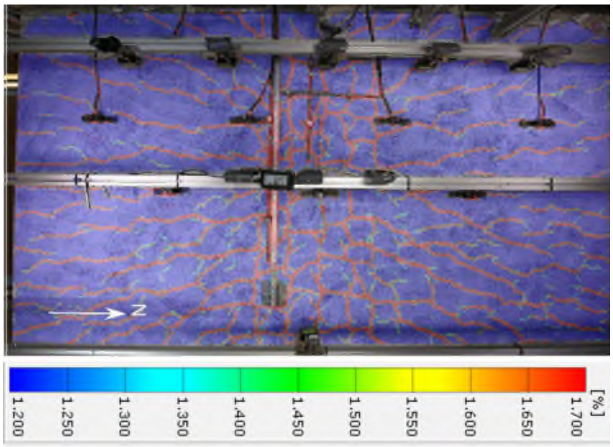


*Figure 20. DIC-processed cracking patterns of SR3M1 at the maximum load.*

## 3.1 Further comparison of test results in a proof loading perspective

Table 1 depicts the approximate loading magnitudes of the described in-situ and laboratory tests. The in-situ bridge tests a), b), h) and i) conducted in the Netherlands and Denmark was loaded with extremely high load magnitudes without causing any distress of the superstructure. The in-situ tests c, d and g had boundary conditions corresponding to beam tests and reached wheel loads ranging from 37-50 tonne. When testing slab configurations, significantly higher wheel load magnitudes were reached; these ranging from 82 tonne in the down scaled OT-slab test to 125 tonne in the Danish in-situ test.

The design load magnitude requirements in Denmark and the Netherlands seem to be significantly lower than the magnitude obtained in the slab tests. In particular when using the requirement of a Danish heavy vehicle class 100, which has the highest characteristic axle load of 15,1 corresponding to a wheel load of 7,6 tonne (23,7 being the highest axle load of the system). Several parameters can have an influence when comparing the crack detections. Monitoring experience and capabilities extensively increased in the projects over time. However, all results indicate a significant margin from crack detection to shear failure. In addition, loads are often placed in critical positions but still provide very high shear failure magnitudes. Even in the pre-stressed OT slab which are known to have higher cracking load than reinforced concrete slabs, a clear margin from crack initiation to failure was still recognized.

*Table 1. NL and DK loading configurations.*

| nr. | Test description [units] | Total Load [tonne] | Axle/wheel Load [tonne] | Note |
|---|---|---|---|---|
| a | Dk, bridge test 1 | 448 | 100/50 | No failure. Applied in-situ test rig |
| b | Dk, bridge test 2 | 465 | 100/50 | |
| c | Dk, Strip 1 | 382 | 97/49 | Yielding, Applied in-situ test rig |
| d | Dk, Strip 2 | 292 | 75/37 | |
| e | Dk, OT-slab | - | -/82 | Yield lines. Applied loading area 350x450mm |
| f | Dk, Slab test | 250 | 250/125 | Shear failure Axle load A-vehicle |
| g | Dk, beam test | - | -/50 | Shear failure, loading are, |
| h | NL, bridge test 1 | 300 | 150/75 | Failure was not achieved, more weight ordered |
| i | NL, bridge test 2 | 400 | 200/100 | No Failure Large settlement of pier |
| j | NL, slab test | 115 | -/115 | Failure, Displacement controlled, loading area |

The non-shear reinforced concrete slabs without prestressing show an even more pronounced margin between the first detected cracks to the ultimate shear capacity. Crack initiation- and patterns could thus be followed throughout the testing procedure; this generating a solid basis for stop criteria evaluation.

## 4 Conclusion and future research

An excellent synergy in the independent testing from the Netherlands and Denmark seems to be present when comparing the portfolio of test results. The compared test results presented in this paper did not indicate any sudden un-warned failure mechanisms when testing non-shear reinforced concrete slabs. High load magnitudes were reached compared to the design loads of the countries. Crack initiations could be detected with a significant margin to the failure magnitude. It was even possible to follow crack developments and formations, opening the possibility to provide stop criteria with a desired margin to possible permanent damage. The margin from stop criterion thresholds to the ultimate capacity limit is still researched. Relating to the tests, the load magnitude seems to be the governing stop criterion threshold in several proof loading cases. However, other stop criteria cannot be disregarded, since this may not always be the case. It should be noted that the applied loading on non-shear reinforced slabs is often specifically placed to generate a shear failure and to investigate the nature of such a failure mechanism. In a representative proof loading, multiple axles will often be applied; this resulting in more pronounced cracks from bending exposure, and thus even better warning. The collaboration between the Netherlands and Denmark has shown how research results can provide a common understanding and perspectivation despite national differences.

## 5 Acknowledgements

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