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Assessment of Corbel Damages in Concrete Parking Structures

N. Assendelft, D.A. Hordijk

Adviesbureau Hageman, Rijswijk, NL

E.O.L. Lantsoght

Delft University of Technology, Delft, NL

Universidad San Francisco de Quito, Quito, ECU

Contact: assendelft@adviesbureau-hageman.nl

Abstract

In the more than sixty years of experience in forensic structural engineering of Adviesbureau Hageman, damages in concrete parking structures in The Netherlands repeatedly passed by. In a study on these damages, mainly based on the comprehensive archive of Adviesbureau Hageman, an overview of the various damages that can be distinguished is made. Furthermore, one category of damages, that is not limited to only parking structures, but generally occurring in concrete structures, is damage to concrete corbels. In order to investigate the behaviour of such corbels under load imposed by the concrete elements that they support, finite element analyses (FEA) are performed with the FE Code ATENA. It was found that damage only occurred in case the bearing material was situated at the edge of the corbel or with an additional horizontal load. In both cases the corbel withstood a rather significant load. In the paper the basic findings of the overview of damages in concrete parking structures and the study on corbel behaviour are presented.

Keywords: finite element analysis; forensic engineering; parametric study; parking structures; reinforced concrete corbels; support end failure

1 Introduction

Damage in concrete parking structures has been a repeated subject over the past 60 years for the Dutch forensic structural engineering firm Adviesbureau Hageman.

Most of the encountered types of damage are frequently observed across various different parking structures. Based on experience, the underlying causes of these damages generally originate from faults in the design or execution stage of the parking structure, suggesting that similar mistakes are being repeated. Although,

research also suggests several causes of damage as a result of degradation mechanisms [1].

One type of damage which is frequently encountered in parking structures is the local damage of concrete supporting elements, specifically corbels, referred to as support end failure [2]. It is characterised by failure of the unreinforced cover of the supporting element, occurring at loads lower than the design load. Although research has shown that this damage does not necessarily compromise the structural capacity of the support element [3], it often leads to costly repair processes.

This research had two main objectives. Its first goal was to provide insight into frequent causes and types of damage that occur in parking structures and discuss potential prevention or mitigation measures. Using forensic reports of damages observed in parking structures in the Netherlands, provided by Adviesbureau Hageman, an overview was gained on these types of damage in parking structures, among other findings. Secondly, it aimed to obtain a better understanding of the behaviour of the support end failure mechanism, exploring its frequent causes, and its behaviour under circumstances not conform design. Using the numerical finite element (FE) software ATENA, the results of experiments from Neupane et al. [3] were used to verify the applied FE-model. Subsequently, the behaviour of the support end failure mechanism was numerically investigated for a few corbel configurations and some of the results are compared with expectations based on a simple analytical model.

2 Overview of damage types

2.1 Data collection

In order to obtain an overview of types of damage occurring in parking structures, a data analysis was performed on 145 forensic reports of damage in Dutch parking structures, dating between 1970 up to 2024. These reports were sourced from the archives of Adviesbureau Hageman, a Dutch engineering consultancy firm. From the content of these reports, several parameters were manually gathered, comprising of the type and cause of damage, the type of structural element it occurred in, the year of construction of the parking structure, the year of observation of the damage, and whether the structure was above- or underground [2].

2.2 Data analysis

From the 145 forensic reports, a total of 234 damages were identified. Damage was predominantly found as cracks, support end failure, spalling, corrosion, and leakage (Figure 1).

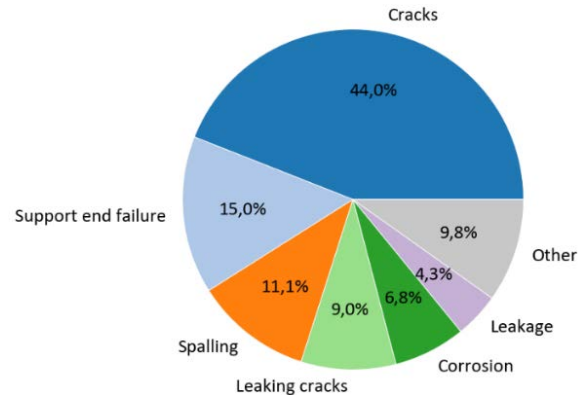


Figure 1. Distribution of the 234 observed damages.

The dataset consisted of an equal amount of above- and underground parking structures. However, the findings indicated a difference in the observed types of damages between these structures. The most significant difference was found in the occurrence of cracks, which accounted for 32% of total damages in aboveground structures and 55% in underground structures, and in the support end failure, which accounted for 22% and 10% for respectively aboveground and underground structures. This may be due to the difference in the applied building method (cast in-situ concrete or prefabricated concrete) between underground and aboveground parking structures.

Additionally, the time between the year of construction and the year damage was observed, was registered (Figure 2). Most of the analysed structures were built after 1990. The results implied that the majority of the observed damage occurs within the first ten years after construction. Therefore, it could be argued that the main cause of damage is predominantly related to faults in design or execution of the structure, as degradation of the structure would be expected to arise as more time passed.

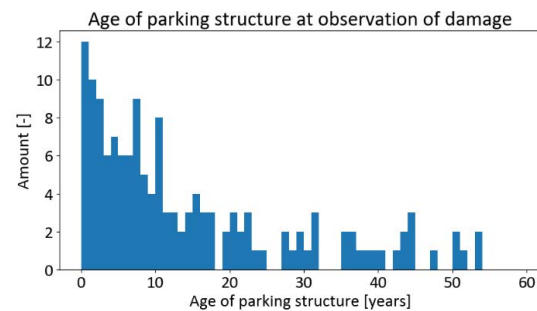


Figure 2. Histogram of elapsed time between year of construction and year of observation of damage.

3 Support end failure

3.1 General behaviour

The results of the data analysis revealed that after cracking in general, support end failure is the second most occurring damage in Dutch parking structures, affecting corbel connections.

Kriz and Raths [4] were probably one of the first to categorise the support end failure as a secondary failure mechanism of concrete corbels. The damage is characterised by the local, brittle failure of the unreinforced concrete cover of a supporting element. Generally, it occurs either along the entire height (Figure 3a) or locally at the corner of the supporting element (Figure 3b).

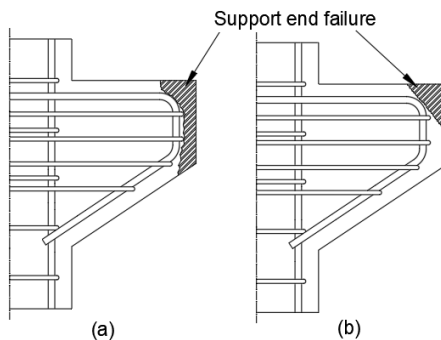


Figure 3. Schematic presentation of potential support end failures.

3.2 Frequent causes

For support end failure two main causes can be distinguished:

1. Horizontal loading on the corbel;
2. Load application on the outer edge of the corbel.

Corbels, when designed and executed in accordance with Eurocode 2 [5], tend to not experience such loading conditions. In practice, however, horizontal loading is frequently caused by imposed deformations and rigid connections between corbel and supported element, particularly in cases involving continuity reinforcement. Furthermore, loading on the edge of the corbel was found to arise due to incorrect placement or movement of the bearing material, and due to limited freedom of rotation of the

supported element. So, the support end failures are generally related to design or execution errors.

4 Numerical study on the support end failure mechanism

4.1 Model validation study

In order to investigate the behaviour of corbels under the aforementioned loading conditions, numerical analyses were carried out using the finite element software ATENA [6]. In a first step, experimental results [3] were used as a benchmark for the modelling assumptions for analysing support end failure.

The results of one of the specimens of the series of experiments by Neupane et. al. [3] was used for verification. In the experiment a symmetric corbel element was loaded until support end failure occurred. The experimental setup of the applied specimen are shown in Figure 4. Support end failure occurred by loading the specimen at the column foot and supporting the cantilevering corbels on its outer edges by steel plates. In the experiment the applied load, the displacement between the steel plates, and the strain of the main reinforcement were measured. Alongside the experiment, Neupane et. al [3] accurately reproduced the experiment using a 3D non-linear numerical analysis.

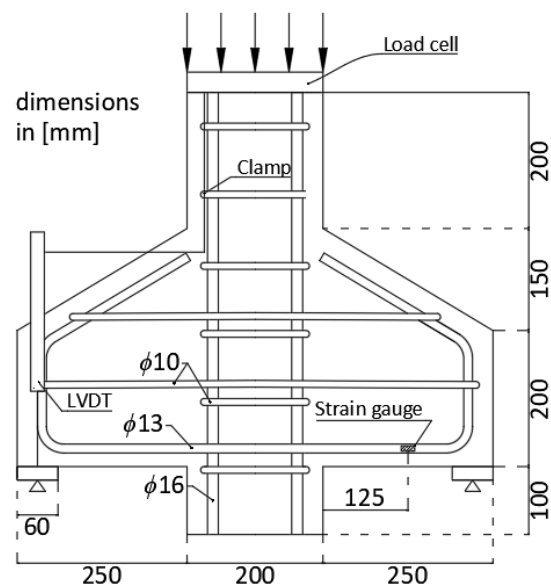


Figure 4. Specimen and experimental set-up series by Neupane et al. [3].

It was investigated whether similar results could be obtained with a 2D non-linear finite element model in ATENA [6]. In the model a fixed crack model [7][8] was adopted, as preliminary analyses [2] revealed that the applied rotating crack model [9][10] could not capture the support end failure. The fracture-plastic model was adopted to model the behaviour of concrete [6]. In the cracked state, the tensile behaviour was described by exponential softening [11]. The behaviour of shear was modelled using the Modified Compression Field theory alongside a variable shear retention factor [9]. The reinforcement was modelled as discrete bars with perfect bond. Furthermore, a mesh sensitivity analysis was carried out with mesh sizes 10, 15, and 20 mm. The corbel was subjected to a displacement controlled load in the middle of the two steel bearing plates. During the experiment, the first crack occurred in the re-entrant corner of the corbel followed by inclined cracks alongside the compressive strut in the corbel (Figure 5). At an applied load of 458 kN support end failure occurred in the experiment. The main reinforcement had not yielded at failure. In the 2D analyses, this behaviour was best captured using a mesh size of 10 x 10 mm. Therefore, this mesh size was used for further analyses.

In Figure 5, the load-displacement of the experiment, 3D numerical model by Neupane et al. [3], and the 2D numerical model are displayed. The numerical results showed similarity to the failure load of the experiment. However, it also showed a disparity in the initial stiffness. Reason is setting of the gypsum layer between the steel bearing pads and the corbel [3].

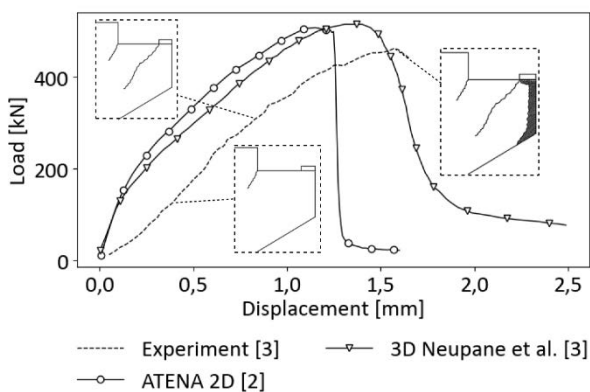


Figure 5. Load-displacement curve [2], [3].

The load-strain relation found with the 2D numerical analysis fits rather well to the experimental result (Figure 6). As can be seen, at failure the reinforcement did not yield, since the yield strain of 0,26 (%) was not yet reached.

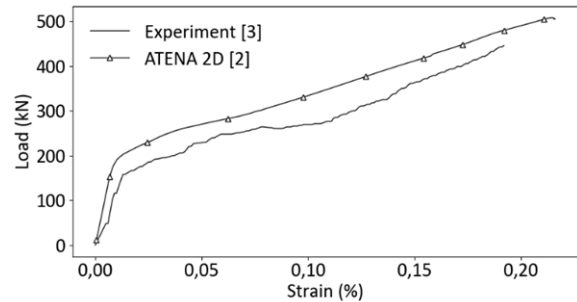


Figure 6. Load-strain relation in main reinforcement [2], [3].

4.2 Parameter study

Next, an exploratory study was carried out to investigate the impact of loading conditions on the corbel failure behaviour. Initially, a corbel was designed in accordance with Eurocode 2, referred to as ‘Eurocode design’, and numerically analysed. The results of that analysis were used as reference for the parameter study.

For the ‘Eurocode design’ a symmetric corbel specimen was designed for a vertical design load of 400 kN. Concrete strength class C40/50 and reinforcement steel with grade B500b was used. Furthermore, an elastomer was used as support material, as it was expected to distribute the bearing stresses more uniform onto the corbel. The configuration of the reference corbel is shown in Figure 7. Furthermore, the corbel had a uniform depth of 300 mm.

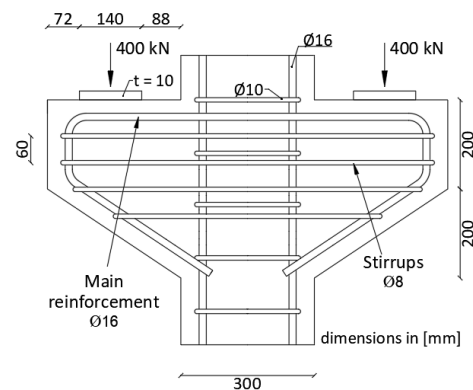


Figure 7. Corbel design in accordance with Eurocode 2 [2].

In the parameter study the effect of a misplacement of the bearing material (towards the edge) and of an additional horizontal load was examined (Figure 8). These loading conditions were chosen partly based on causes of support end failure occurring in practice, as obtained by the data analysis. Furthermore, these were chosen because misplacements of supports without any damage in the corbel often leads to discussions in practice as far as the effect on the corbel behaviour is concerned. The three configurations are, respectively, the bearing pad placed on the edge of the corbel (a), a bearing pad on the edge and reduced in width (b), and combined horizontal and vertical loading (c) (Figure 8).

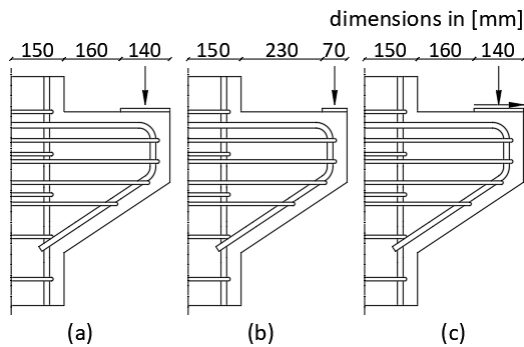


Figure 8. Corbel loading conditions as applied in parameter study.

Configurations a and b reflect situations from practice such as the ‘walking’ of support material during a structures’ lifetime or incorrect placement of the support during execution. Moreover, configuration c represents horizontal loading due to imposed shrinkage of the supported element, which in practice is probably the most frequent occurring reason for corbel damage.

Minor changes were made in the numerical model with respect to the validation model. A deformation-controlled analysis was applied for configurations a and b, whilst the analysis of configuration c was force-controlled. The applied deformation was uniformly distributed over the entire width of the top of the elastomeric support element. In configuration c, the horizontal load was applied via an additional concrete element placed on top of the elastomer supports in order to accurately reproduce the interaction of stresses between the supported element, the bearing pad and the corbels.

4.3 Results

In the numerical analyses, the corbel configurations were loaded until failure. For the Eurocode design, configurations a and b, this was achieved by applying the vertical load in a deformation-controlled way, in which the deformation at both corbel sides were equal. For configuration c, the vertical load was increased until it reached the design load of the corbel of 400 kN, after which a horizontal load was introduced and incrementally increased.

The load-displacement relations obtained from the numerical analyses are presented in Figure 9. For the corbel configuration according to Eurocode design the maximum load that could be applied, was 826 kN. After the peak load the displacement was further increased till failure occurred at a load of 748 kN. For configurations a and b, in which the elastomeric support was positioned on the edge of the corbel (a) and also reduced in size (b), a maximum load, corresponding to the failure load in practice, of respectively 623 kN and 372 kN was obtained, whilst the configurations failed at a load of respectively 599 kN (a) and 353 kN (b). The maximum load and failure load of configuration c occurred at a horizontal load of 69 kN.

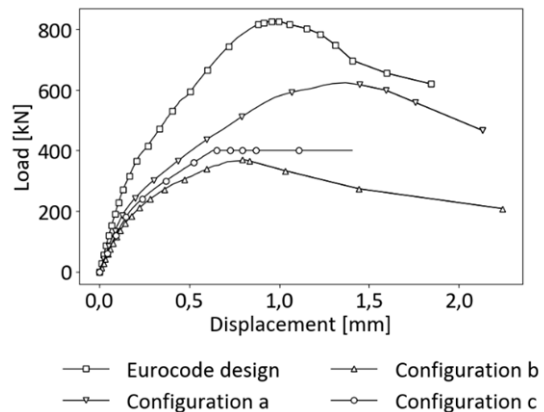


Figure 9. Load-displacement relations for the Eurocode design, configurations a, b and c.

The crack pattern at failure for the Eurocode design and configurations a, b and c is given in Figure 10. The failure mechanisms of the corbel configurations changed in response to adjustments in the design. The first cracks in the Eurocode design occurred at the re-entrant corner of the corbel, followed by splitting cracks along the compressive strut.

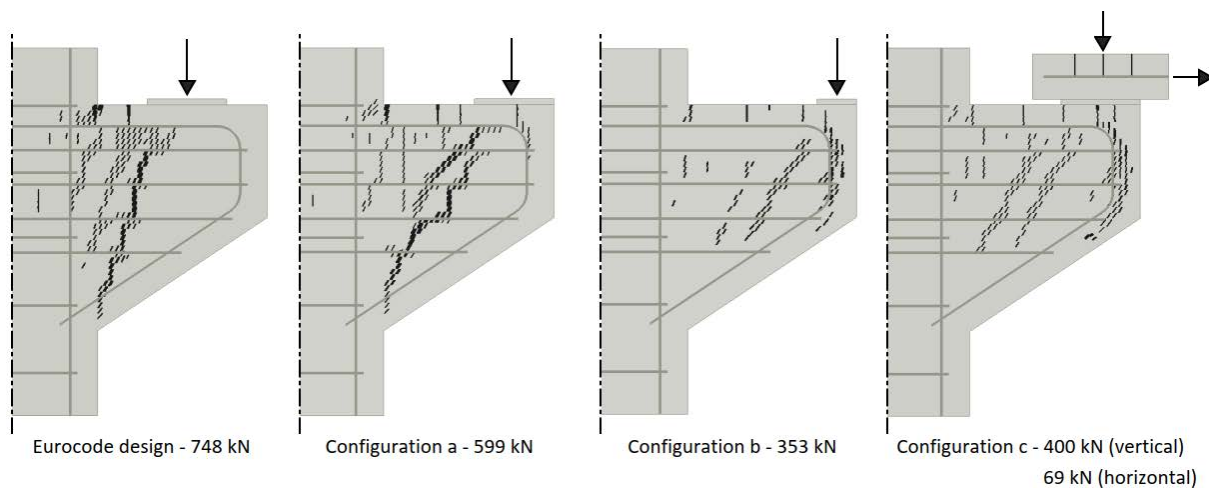


Figure 10. Cracks in numerical model at failure load for Eurocode design and configurations a, b and c (cracks with a crack width larger than 0,05 mm are shown).

The latter eventually led to the failure of the corbel. A similar crack development and failure was observed for configuration a, along with some additional cracks related to a support end failure. For configurations b and c, the corbels failed by support end failure.

A closer inspection of the failure mechanism of configurations b and c showed a noticeable difference in the tensile stresses in the main reinforcement, as compared to that for the Eurocode design (Figure 11), especially in the vertical bent section at the outer ends of the corbel (at the elliptical sections in Figure 11). Crack propagation along the vertical section of the main reinforcement, in configurations b and c, resulted in increased tensile stresses of the main reinforcement in this region up to 200 MPa. In contrast, near-zero tensile stresses were observed in this section of the main reinforcement for the Eurocode design.

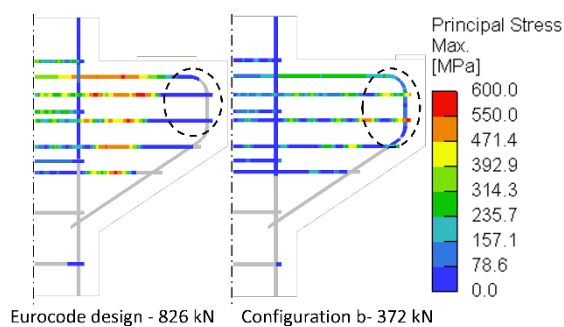


Figure 11. Tensile stresses in the main reinforcement at maximum load for Eurocode design and configuration b.

For both configurations b and c, the support end failure crack propagated over the entire height of the corbel, as was suggested to be a potential failure plane in Figure 3 (a), rather than the local failure of the corner. This behaviour resulted from increased compressive stresses in the unreinforced cover of the corbel, caused by a disruption of the principal stress trajectory below the bearing pad due to the crack development. This process continued iteratively until the bottom of the corbel was reached and the cover over the total corbel height failed. A depiction of this process is provided in Figure 12.

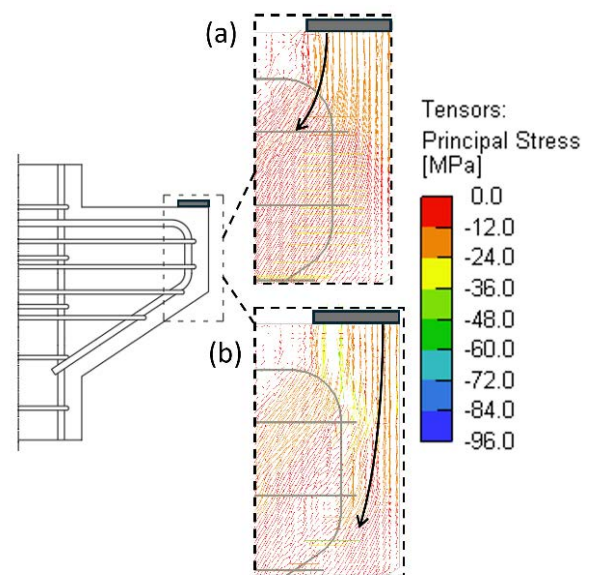


Figure 12. Development of principal compressive stress trajectories at 328 kN (a) and 372 kN (b) for configuration b.

5 Analytical approach

In the consulting practice of Adviesbureau Hageman once the capacity of a corbel with an elastomeric bearing material at the edge was assessed, based on the resistance of a shear interfaces according to Eurocode 2 [5] section 6.2.5, shown in Eqn. (1). For configuration b it was investigated to what extend the failure load according to FE-analyses differs from that of such an analytical model.

$$v_{Rdi} = c f_{ctd} + \mu \sigma_n \quad (1)$$

The resistance of the shear interface can be calculated by assuming an arbitrary failure plane. In Figure 13, a free body diagram is presented of such failure plane for configuration b.

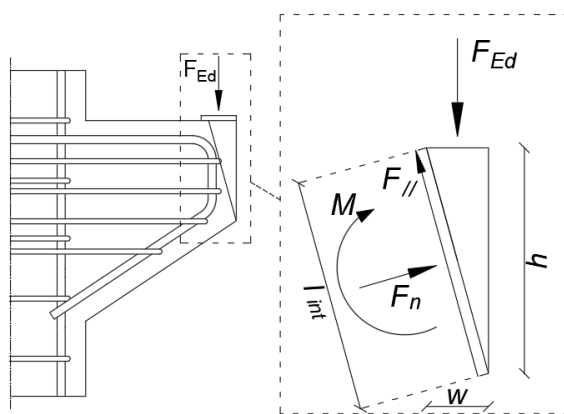


Figure 13. Free body diagram of shear interface for configuration b.

Acting on the failure plane is a shear force ($F_{//}$), normal force to the plane (F_n), and a bending moment (M). The forces and stresses on the free body diagram can be calculated by Eqns. (2-3).

$$F_n = \frac{w}{l_{int}} * F_{Ed} ; \sigma_n = \frac{F_n}{l_{int}} \quad (2)$$

$$F_{//} = \frac{h}{l_{int}} * F_{Ed} ; \sigma_{//} = \frac{F_{//}}{l_{int}} \quad (3)$$

Using this method, a capacity related to shearing off a corner of the corbel, could be estimated, based on assumptions for the roughness factors for the failure plane and the mean tensile strength of the applied concrete.

This analytical calculation was performed for configuration b [2]. The dimensions of the failure

plane were estimated as height (h) is 200 mm, width (w) is 55 mm, and interface length (l_{int}) is 208 mm. A rough interface is assumed, resulting in roughness factors c and μ of 0,45 and 0,7, respectively [5]. The mean tensile strength (f_{ctm}) is 3,5 MPa, based of concrete strength class C40/50. For these values, with the analytical model for a vertical load and configuration b a capacity of 113 kN was calculated [2]. For comparison, the failure load obtained by the numerical analysis was 372 kN. So, the applied analytical model is very conservative and, as was seen in the numerical analysis, shearing off a corner of the corbel was also not the failure mechanism.

6 Discussion

This study investigated frequently occurring damages in Dutch parking structures and provided some insight into behaviour of the support end failure mechanism.

The findings of the data analysis implied that most the observed types of damage, in Dutch parking structures, occur within 10 years after construction. Therefore, it indicates that these are predominantly arising from mistakes in the design or execution stage of a structure. Although, observations of degradation induced damage might increase in the future, due to the large amount of structures that is built after 1990. As only a limited number of forensic files were used in the data analysis, it affects the generalizability of the results.

With the applied numerical analyses insight was gained in the behaviour of corbels under various loading conditions. Especially the analyses for loading circumstances, not according to a Eurocode design, but rather often seen in practice, resulted in interesting results. It was found that even with the elastomeric bearing material at the edge of the corbel, still a rather large capacity was found. Though it is realised that in practice even more circumstances, for example a translation and/or rotation of the supported element, may affect the load at which failure occurs.

7 Conclusion

In order to provide insight into types of damage in Dutch parking structures, a data analysis was carried out on forensic reports of damages. Furthermore, to assess the behaviour of support end failure, numerical analyses, studying various corbel loading configurations, were conducted. The main conclusions are:

1. The findings of the data analysis of forensic reports from Adviesbureau Hageman in The Netherlands, indicate the three most common type of damage in parking structures, being cracks, support end failure, and spalling. Most of the encountered damages were found to be predominantly caused by faults in the design or execution stage. Additionally, there appeared to be a difference in frequency of occurrence of cracks and support end failure, for respectively above- or underground structures.
2. It was confirmed through validation of experimental studies that the support end failure can be accurately modelled using a 2D finite element model. In the applied analyses it was found that a fixed crack model had to be used in order to capture this failure mechanism.
3. It was established in the numerical analyses that placement and size of bearing support and applying horizontal loading contribute to initiation of support end failure. However, in cases where support end failure occurred, configurations b and c, the design load of the corbel (400 kN vertical load) was almost reached or even exceeded for mean material properties and without safety factors.
4. The numerical analyses of configurations b and c showed that support end failure cracks continued over the entire height of the corbel. It was found that this behaviour is caused by the initial support end failure cracks, which reroute the compressive strut of the corbel through the unreinforced cover, inducing tensile

splitting stresses in the unreinforced cover, over the entire height of the corbel. The failure load appeared to be significantly higher than the capacity as it was found with a simple analytical model for shearing off a corner of the corbel.

5. For design and execution of parking structures it is important to pay sufficient attention to the correct position of the elastomeric bearing material and possible consequences of imposed deformations.

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