Assessment of the structural safety of reinforced concrete balconies

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Summary
This paper reports about the structural safety of cantilevered reinforced concrete balconies of apartment buildings in the Netherlands. The concrete floor of this type of balconies is between 80 mm and 150 mm thick. This type of balconies was mainly constructed between 1950 and 1970. After a collapse of a balcony situated at the 9th floor level of an apartment building, investigations started to the causes. Pit corrosion of the reinforcement, induced by chlorides, had reduced the cross section of reinforcement steel. Besides that, the position of the reinforcement was 10% lower as prescribed in the design and the permanent loads were 28% higher as assumed in the design. As follow up, the structural safety of another eleven buildings with similar balcony structures were assessed. In six of the eleven buildings measures related to structural safety had to be taken. It was clear that owners of this type of building in the Netherlands need to assess the risk of lack of structural safety. To promote an efficient assessment of the structural safety, a step by step method was developed. In the step by step method three specific risks are evaluated: pit corrosion, a lower position of the reinforcement as described in the design and higher permanent loads as assumed in the design. For the assessment of existing structures, lower partial safety factors are used. With drawings and calculations of the structure and the results of non-destructive tests a first check of the structural safety can be done. After that, the sensitivity of the structure to cracks and corrosion of the reinforcement are estimated. If the sensibility is low, further investigations are postponed, if not further investigation into the presence of chlorides and corrosion rate is necessary. The assessment ends with a conclusion: the structural safety meets the requirements or measures have to be taken.

Keywords: assessment of structural safety, existing structures, balconies, multi apartment blocks, corrosion of reinforcement steel

1. Introduction
In May 2011 a cantilevered concrete floor plate situated at the 9th floor level of an apartment building in Leeuwarden, the Netherlands collapsed; the floor plates below also collapsed due to the impact of the falling weight (fig.1). Fortunately there were no injuries. The building was constructed in 1965. Before the collapse there were no signs indicating a structural defect. The collapsed plates were part of the balcony corridors that lead to the entrance of the apartments. Because of doubts about the structural safety of the other cantilevered concrete plates the owner decided to evacuate the residents. A first inspection showed corrosion of the reinforcement in the fracture surface. The decision was made to demolish the cantilevered concrete plates and to replace them by a new structure. After this decision, a more intensive research was done to the causes of the collapse. It was concluded that pit corrosion of the reinforcement was the cause of the sudden collapse; a lower position of the reinforcement and permanent loads higher than assumed in the design were also of influence.

Following to these conclusions two housing associations decided to assess the structural safety of similar balcony structures of another eleven apartment buildings. These assessments led to the conclusion that in six of the buildings measures related to structural safety had to be taken.
With these results it was clear that in general owners of this type of buildings in the Netherlands need to assess the risks of a lack of structural safety of the balconies. This type of buildings was mainly built between 1950 and 1970. Later, balcony structures were designed in a different way, to improve thermal isolation and to reduce condensation problems.

To promote an efficient assessment of the structural safety of balconies, a step by step method was developed that was based on the knowledge and experience from the already performed investigations [1].

In the next the results of the investigations will be explained. After that, the specific risks as pointed out, the methods to get information to assess the structural safety and the applicable codes will be discussed. The step by step method to organize and execute the assessments is explained and some examples of measures in case of disapproval are given.

2. Results of the investigations

The investigation to the causes of the collapse was done by a team of consulting engineers. Information was collected from archives, from the administrator of the building, by doing tests on concrete samples and reinforcement bars and by making analyses. It was concluded as follows. The collapsed cantilevered floor plate (fig. 2) had a thickness of ca 130 mm; on top were a finishing layer and a poly-urethane finish, which were applied during a renovation 10 years before the collapse. The fracture surface of the concrete plate to the concrete beam, just under the facade wall of the apartment, showed an older crack due to bending. It is plausible that the crack originated during construction of the building. The reinforcement in the plate consists of bars with a diameter of 6 mm and a centre-to-centre distance of 100 mm. Local pit corrosion of the reinforcement bars at the position of the crack reduced the cross area, the tension capacity and the deformation capacity of the bars. Checks of the position of the reinforcement bars showed that their position was lower as designed (average 87 mm above the underside of the plate instead of 97 mm). Checks of the permanent loads showed that this loads were higher than assumed in the design (3.6 kN/m² instead of 2.8 kN/m²).

Tests showed chloride concentrations of > 1%, weight to weight, in the concrete and a profile of chloride concentrations that decreased with the distance to the top of the plate. The chlorides are believed to originate from de-icing salts, used during winter conditions. Water with chlorides must have penetrated the crack and caused the pit corrosion in the reinforcement bars. Mainly due to the reduced cross area of reinforcement steel and secondly due to the smaller effective depth of the rebar, the bearing capacity of the cantilevered plate was reduced to a level lower than required for the permanent loads. After friction forces, bending tension strength of the
concrete and bearing capacity of the handrail gave up, the plate broke off without warnings. The rust, not visible from the outside, was clearly visible in the fracture surfaces. The rust must have been not voluminous enough for pushing the concrete cover off.

Fig.2: Typical section of cantilevered balconies (apartment buildings built between 1950-1970)

The results of the assessments of eleven other apartment buildings with cantilevered plates were as follows. In three cases increased chloride concentrations were detected, corrosion of the reinforcement had started and reached a degree that was significant; penetration of chlorides was only found in balcony corridors, not in private balconies. In three other cases, the lower position of the reinforcement than prescribed in the design has led to disapproval. In the other five buildings, the structural safety meets the requirements.

3. **Specific risks of the structural safety of the balconies**

Based on the results of the investigations of the collapsed floor plate and the investigations of the cantilevered floor plates of eleven other apartment buildings, it was concluded that there are three specific risks and that these risks could not be evaluated by the usual visual inspection only:

- Pit corrosion of the reinforcement
- A lower position of the reinforcement bars as designed
- Higher permanent loads from finishing layers and/or thickness of the plate than as assumed in the design

Pit corrosion only seems to be a risk for the balcony corridors (it is plausible that de-icing salts are not used on private balconies). The other two risks apply to both.

Pit corrosion will start after chlorides have penetrated the concrete and have reached the reinforcement steel. Once this process is started it will go on, even if no new chlorides are penetrating. The concentration of chlorides that can lead to pit corrosion is supposed to be > 0.4 %. Without cracks in the concrete, the penetration of chlorides is much slower than with cracks [2]. So the risk of pit corrosion of the reinforcement steel of the cantilevered plates depends on the risk of cracking and the presence of chlorides. Pit corrosion leads to reduction of the cross area of reinforcement steel and therefore to a lower bending moment capacity of the plate and to a loss of deformation capacity and so to a more brittle behaviour in case of collapse.

A lower position of the reinforcement can be caused by insufficient support of the reinforcement during the execution and the pouring of the concrete. A lower position of the reinforcement leads to a lower bending moment capacity of the plate and can also lead to a brittle behaviour in case of collapse (that occurs if the moment capacity based on bending tension strength of the concrete becomes significant higher than the bending moment capacity based on the reinforcement of a cracked section) [3]. The presence of higher permanent loads than designed for, can be caused by wrong assumption in design, inaccurate execution and/or by changes during operation. Higher permanent loads lead to lower structural safety.
4. **Gathering the necessary information for reassessing the bearing capacity**

Drawings and calculations of the structure and the reinforcement, if available, are of great help. Of course one has to be aware that changes may have been made during the execution. With non-destructive tests the location of the rebar can be detected and the dimensions of the plates can be determined. The diameter of the bars can only be estimated by this way; to be sure, local visual inspections through removing the concrete cover are necessary. The steel quality can be assumed as indicated on the drawings. In case of lack of information or in case of doubt, some parts of bars have to be taken from the structure (outside the critical zone) to determine stress-strain diagrams. After the information is collected, calculations of the structure can be made, based on the assumption that there is no corrosion. If the structure fits the requirements the next step is to consider the risk of pit corrosion. Based on the experience in executed investigations, this is only necessary for balcony corridors, not for private balconies.

By calculation of the bending tension stress in the concrete plate due to the permanent and imposed loads, the probability of cracks can be evaluated. In the absence of cracks the probability of pit corrosion can be neglected. Of course with checking the bending tension stress, the bending tensile strength has to be assumed at the safe side, which means values for young concrete and according to the concrete quality as used.

If bending cracks cannot be excluded, concrete samples must be tested to determine the chloride concentrations and chloride profiles. Visual inspections on the presence of cracks in the samples can be done. If the chloride concentrations at the level of the reinforcement are higher than 0.4 %, or cracks are visible corrosion may have started. Further investigations to the presence and the degree of corrosion have to be done. By doing potential measurements, information about possible locations of corrosion activity can be gathered. For executing potential measurements it is necessary to demolish the finishing layers in the parts to examine. With the results of these measurements the suspected bars must be visual checked by removing the concrete cover.

The tests to determine chlorides and the use of potential measurements lead to higher costs for the owner and inconvenience for the residents. It is proposed to avoid this for structures where the risks are relatively small due to an excess of reinforcement, resulting in a robust behaviour. This can be checked by calculations of the structure with an assumed degree of corrosion. If these calculations lead to approval, further examinations can be postponed.

![Graph](image)

**Fig. 3: Reduction of the cross section of reinforcement steel due to corrosion**

The assumed degree of corrosion is based on the next assumptions:
- the process of corrosion has started 25 years after construction
- 50% of the bars is partly corroded,
- the velocity of corrosion is 0.05 mm each year
Fig. 3 shows the results for the percentage of the remaining cross section of the reinforcement steel. If a calculation with the reduced cross section of the reinforcement leads to approval of the structural safety, the risk of lack of structural safety due to corrosion is assumed to be negligible. Most structures from 1950-1970 that were correctly constructed and calculated with the then prevailing codes and to which no major changes were made, will be approved this way, due to the lower partial safety factors which can be used nowadays for existing structures (see par.5).

5. **Existing structures and codes**

For new structures the Eurocodes [3] with national annex (NA) give rules for the structural safety. The Dutch NA to EN 1991-1-1 prescribes an imposed load of 2.0 kN/m² for corridors and 2.5 kN/m² for private balconies. The structure must also be checked for a point load of 3.0 kN and a line load of 5.0 kN over 1 m. The partial safety factors are prescribed, for buildings based on an expected live time of 50 years. The Eurocodes don’t give detailed rules for assessment of existing structures yet.

It can be motivated that for the assessment of existing structures an approach with lower factors is acceptable [5], [6]. In the Netherlands assessment of structural safety of existing structures is done by using the recently developed code NEN 8700 [7]. The building regulations refer to this code and require only a check of the ultimate limit state (ULS). Approval or disapproval of existing structures is based on ULS calculations with a life time of 1 year for the material behaviour and 15 years for the loads. Depending on the objectives of the owner of the asset, checks of ULS based on a longer period than one year can be advisable, as well as checks of service limit state (SLS).

6. **Assessment step by step**

The assessment method was developed and discussed in a committee of owners, governmental authorities, structural engineers and material experts. The starting point was a risk based assessment which reduces costs of investigations, if that is justified. Inspections that need chopping and crushing are relatively expensive, lead to nuisance for the residents and can influence the trust of residents in the building structure.

In fig. 4 the flow chart of the summarized assessment procedure is given. The risk based assessment is clearly illustrated in step 3b:

- In all cantilevered plates in which bending cracks due to permanent and imposed loads are not expected, this means the concrete sections are expected to be free of cracks, the risk of loss of bearing capacity due to corrosion is neglected. As checked in step 3a, the structure meets the requirements of existing structures.
- In all cantilevered plates with a robust reinforcement the risk of loss of bearing capacity due to corrosion is neglected for this moment. The reinforcement is assessed as robust in the case that the structure meets the requirements of ULS with a reduced area of the reinforcement; the reduction of the reinforcement is based on assumptions of the corrosion process (fig.3).

In [1] there are advised rules for the number of examinations that have to be done in a building.

7. **What if the structure does not meet the requirements of structural safety?**

If the assessment leads to the conclusion that the structure does not meet the minimum requirements for structural safety of existing structures, measures have to be taken. It can be helpful to differentiate measures for the short term and for the longer term. Of course it is wise to keep in mind why the structure is disapproved. Pit corrosion will lead to local constriction of the reinforcement bars, and by that, will reduce deformation capacity and will show brittle behaviour in case of collapse. With overload due to higher permanent loads and /or lower position of the reinforcement only, the structure could be able to show deformations and wide cracks before collapse.

For the short term a restriction of the imposed load can be acceptable; it must be sure that residents and visitors of the building understand the announcement of the restriction. The structural safety can for the time being also be provided by introducing another or second way of load bearing (e.g. by temporary struts).
For the long term replacement by a new structure, reducing the overload or strengthening of the structure can be considered. By replacement of the cantilevered floors the building can be upgraded with regard to functionality and aesthetic view. In some cases the decision was made to demolish the complete building because the bad functionality of the building makes investments in renovation of the structure not attractive; in those cases redevelopment has lead to a better outcome.

Fig. 4: Flow chart of the assessment of structural safety of balconies of existing apartment blocks
8. Remarks

Due to the Dutch building laws and regulations the owner is responsible for the structural safety of the buildings in his possession. But the probability that he is confronted with structural safety questions is relatively small. Perhaps this is the reason that the as-built documentation of building structures is, generally spoken, not very well organized. Most owners of buildings are not aware of the usefulness of concrete and reinforcement drawings and calculations until they need them for renovation or safety problems. Engineering and construction firms keep the information normally only during the time of their responsibility; the information can even disappear earlier due to take-overs or ending of the activities. Local government normally keeps the information of the structures as far as related to the building permit, but they also have problems in tracing the documentation due to re-organizations and mergers. It is clear that lack of as-built information leads to more intensive and expensive inspections, necessary for an assessment.

The assumptions of the corrosion degree according to fig. 3, which is used in the step by step method, are rather arbitrary. But with these assumptions, it is possible to separate the structures with the highest risks from the others. It is planned that the step by step method will be evaluated after 2 years. This could lead to changes in the assumptions of the corrosion degree and the proposed step by step method of assessment.

References

[7] NEN 8700 (in Dutch)