Ponding collapse analyses of light weight roof structures by water raising capacity

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Local collapse of flat light weight roof structures due to ponding frequently occurs in the Netherlands. In the article the circumstances under which ponding occurs, are described. The term 'water raising capacity' is introduced and defined as highest water level that can be achieved on the structure. This water raising capacity is used for explaining local collapses due to ponding by analyses and for design to prevent structures to collapse due to ponding.

Key words: Flat roof collapse, ponding, water raising capacity

1 Introductions

Adviesbureau Hageman has an experience of over 25 years with the analyses of partial collapse of roof structures due to ponding. In this paper ponding is defined as the local accumulation of water on a roof due to the deformation of the roof structure that is caused by the weight of the water. A list of collapses considered by Adviesbureau Hageman is part of a report about the collapse of light weight flat roof structures of the Dutch Department of Housing (*Kool, 2003*). This report contains 93 cases in the period 1990 until 2002. A description is given of the circumstances under which a local collapse due to ponding can occur. Also the term 'water raising capacity' will be introduced.

2 Circumstances related to rain

Local collapse of a light weight structure due to ponding only occurs in certain particular situations. Accumulation of water on a light weight flat roof can only cause a collapse, when the next two rain related circumstances are fulfilled:

- a failure of the regular rainwater drainage system;
- the intensity of the rainfall is very high.

A failure of the regular rainwater drainage system can be the case on the roof itself or remote in the drainage system.

Figure 1: Example of a roof after a local collapse due to ponding

Figure 2: Examples of blocked rainwater gullies

When, after a local collapse, an observation of the roof is carried out, it is often found that the gullies of the regular rainwater drains are fully or partial blocked by leafs, feathers or other materials (Figure 2).

When the rainwater drainage system is connected to the public sewer without the use of a waste or an overflow, malfunction of the sewer system can lead to a reduction of the capacity of the system so that rainwater is stored on the roof during heavy rain fall.

Under normal weather conditions the intensity of the rain in the Netherlands is limited so that a not properly working rainwater drainage system will not lead to the storage of a large amount of water on the roof. The high intensities of rain that may cause collapse in general only occur during the summer season when, after a period of rather high temperatures, thunderstorms occur. During these thunderstorms the intensity of the rainfall is high and can be seen by radar. An example of a radar picture showing rain intensities is given in Figure 3. In general the radar is capable to distinguish between different intensities up to an intensity of 30 mm/hour. All intensities which are higher, are indicated with the same colour.

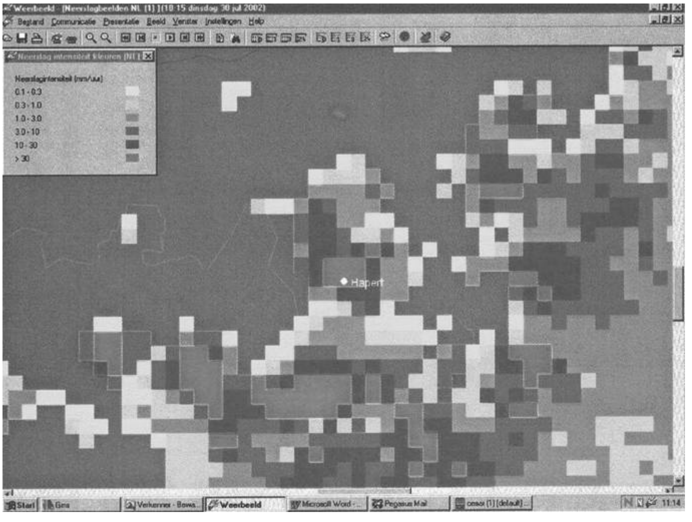
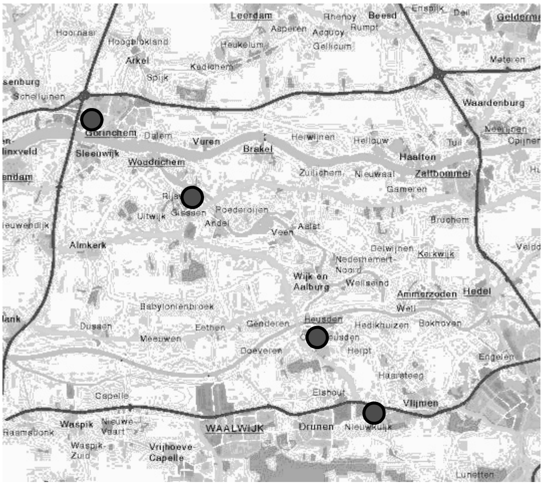


Figure 3: Example picture of rain intensity created after radar measures

The appearance of the thunderstorms is very local and objects in which local collapse occurs during a thunderstorm are generally located close to each other. As an example the map in Figure 4 shows four known damage locations on a line that occurred in the evening of June 29th 2005 during a thunderstorm that slowly moved from the south-east to the north-west. From the list in (*Kool*, 2003) it can be derived that the situation of June 29th is no exception. It is often the case that several damages occur on the same date and in the same part of the country. From the KNMI (Dutch meteorological institute) the rain intensity numbers presented in Table 1 are received.



location of a roof structure that partly collapsed on 29 June 2005

Figure 4: A thunderstorm caused four local collapses on a line

Table 1: Maximum amount of rainwater (mm) in a time interval and its frequency of exceeding (KNMI 2005)

frequency of exceeding	minutes			
	5	15	30	60
once every 10 years	10	18	23	27
once every 20 years	12	21	26	31
once every 50 years	14	25	31	37
once every 100 years	15	28	35	42

From these numbers it can be concluded that the duration period of those thunderstorms is short. The difference between the amount of rain possible within 30 minutes and the amount of rain possible within 60 minutes is less significant than the difference between the shorter time periods.

3 Circumstances related to the structure

3.1 *General*

Local collapse due to ponding in general only occurs for a particular group of buildings. In general the following four requirements for such a building can be formulated:

- it has a flat roof;
- the permanent load on the roof structure is limited;
- the roof surface has a large area;
- the water raising capacity of the roof structure is limited.

The last requirement will be discussed in Section 4. Hereafter the other three requirements will be discussed.

3.2 *Flat roof*

In the Netherlands so called flat roofs are not exactly flat. At least in one direction there will be a small slope to cause that rainwater will flow from the roof surface to the rainwater drains. In (NEN 6702, 2001) a slope of 1,6 % is advised. The slope of a roof structure can be created by varying the column lengths, by creating a camber in the beams or by a combination of these two.

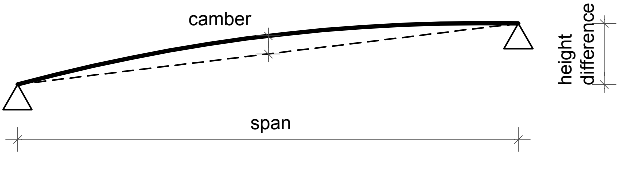


Figure 5: Slope caused by height difference and camber

In general, the advised slope is present in structures where a collapse occurred. Sometimes the slope is less. This can be the case with roof structures, built in a time when a slope of less than 1,6% was advised. But also construction errors sometimes caused a smaller slope. Such errors can be an incorrect height of the column or not providing a camber when it was required by the structural engineer.

3.3 *Light weight structures*

The required strength and stiffness of a roof structure is depending on the load. The load on the roof structure is caused by the permanent load and the variable load that has to be

taken into account. Collapse due to ponding occurs in structures with a limited permanent load. The roof cladding is generally provided by profiled steel sheets or light weight sandwich panels. The other parts of the structure often consist of steel beams. The permanent load on these structures is often not more than 0,20 kN/m². For the structures considered here the characteristic value of the variable load is approximately 0,50 kN/m². The partial safety factors for the load are 1,2 for the permanent load and 1,3 for the variable load. Due to the limited value of the permanent load, the absolute difference between the characteristic load, 0,2 + 0,5 = 0,7 kN/m², and the design value of the load in the Ultimate Limit State, 1,2×0,2 + 1,3×0,5 = 0,89 kN/m², is only 0,19 kN/m² (19 mm of water). So, with only a limited additional load there is situation where collapse can occur.
Furthermore, in the Netherlands in the design of the roof structure the stiffness is often governing for the size of the beams. When the deformations by the permanent load is compensated by a camber in the beam, according to NEN 6702 the stiffness of the structure should be so that the additional displacement caused by the variable load is not larger than 1/250 of the span. The effect of this on the behaviour during the accumulation of water will be discussed later.

3.4 Large area

In general roof structures are designed for a variable load of 0,5 to 0,6 kN/m². The water height equivalent of this is 50 to 60 mm's. To cause local collapse in a structure, significantly more water than this 50 mm's is required. From Table 1 it can be seen that it is very unlikely that this amount of rainwater will fall on a particular square meter within a short period of time.

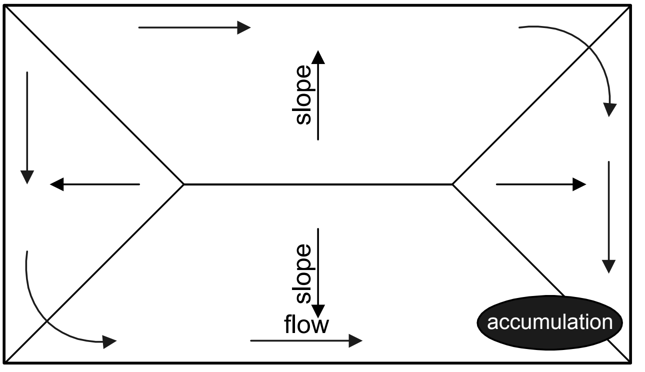


Figure 6: Flow of water on a roof to the area where accumulation takes place

However, when water from other parts of the roof surface flows to one place (water accumulation), then, at the end the collapse will occur there. Theoretically, rainfall is possible that causes small roofs to collapse. However, practically, only on roofs with a large surface area the amount of water is sufficient to achieve such a local collapse.

4 Water raising capacity

4.1 ***General***

The response of a roof structure to a load caused by the storage of water on the roof is not linear to the water level or the water on the roof. Similar as with stability of columns the response is depending on the deformation of the roof structure. In case of the same water level on the roof with a less stiff roof, is obvious that the total load is larger, because the deformation of the structure is larger and so there is more volume for water.

Similar to the analyses of the stability of a column the response of the roof structure can determined with analytical methods or by an iterative method. An analytical method is described by (Blaauwendraad 2005 and 2007). For analysing the several collapses in practice the author has developed software in which an iterative method is used. Hereafter the results of a calculation performed with the software for this latter method is presented. It is particular for this program to perform the analysis of the response of the structure not for a defined water level but for a defined volume of water, that is stored on the structure considered. By a two dimensional analysis of the structure the volume of the stored water is divided by the width considered. This results in an area of the cross section of water over the span of structure. Starting point in the program is a certain (two-dimensional) cross-sectional-area of the water. Based on the own height position (slope and camber) of the structure the water level that corresponds to this cross-sectional area of water can be calculated. With the water load, found in this way, the deformation of the structure can be calculated. This will lead to an adjustment of the height position of the structure and so also to an adjustment of the water level. This procedure will be repeated for the chosen water cross-sectional-area (volume of water) until the water level on the roof or the height position of the beam does not change significantly anymore. Then the deformation of the roof and the corresponding water level for that water volume is found. Subsequently the procedure is repeated for a larger water volume.

4.2 *Example*

The structure considered is given in Figure 7. It is a structural principle that is used often in a two bay hall. Above the middle support a higher profile is used for the larger hugging moment there.

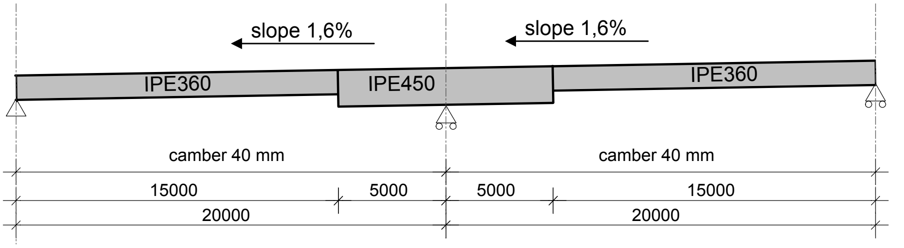


Figure 7: Structure considered, centre-to-centre-distance of adjacent beams is 5000 mm

The results of the ponding calculation can be summarized in three graphs:

- a graph which gives the deformed shape of the structure depending on the volumes of water;
- a graph which gives the internal moments in the structure depending on the volumes of the water;
- a graph which gives the relation between the water level on the roof and the volume of water stored on the roof.

These graphs are presented hereafter in the Figures 8 to 10. The first two graphs give a description of the lower span of the structure only. The position at 0 meter is the initial lowest point of the structure at the end support. The position at 20 meters is the middle support of the continuous beam. The behaviour described for 0 m^3 is that due to the permanent load only.

The third graph shows that the water level above the original lowest point of the structure will not be higher than 105 mm. When this level is reached - with 4 m^3 water stored over the considered width of 5 meter - the water level will decrease with further increasing amount of stored water. From that volume on water from other parts of the roof will flow to the place considered, as shown in Figure 6. When the maximum water level is reached the stresses in the steel structure will often not be critical. The behaviour of the structure is still elastic. The elastic moment capacity of the IPE 360 beam is equal to 212 kNm. As can be seen in Figure 9 in this case the moment capacity will be reached when 7 m^3 is stored.

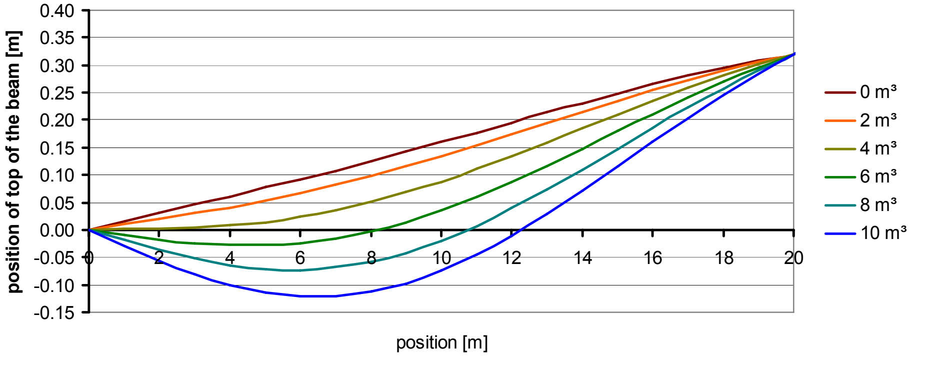


Figure 8: The deformed shape of the structure depending on the volumes of stored water

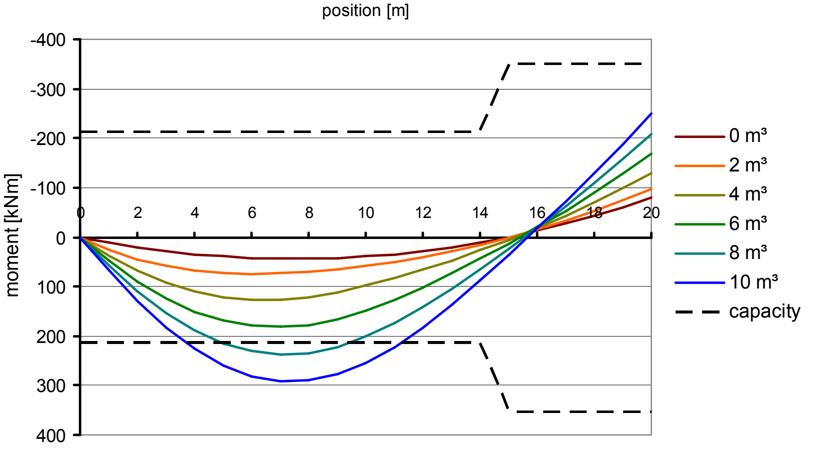


Figure 9: The bending moments in the beam as function of the volume of stored water

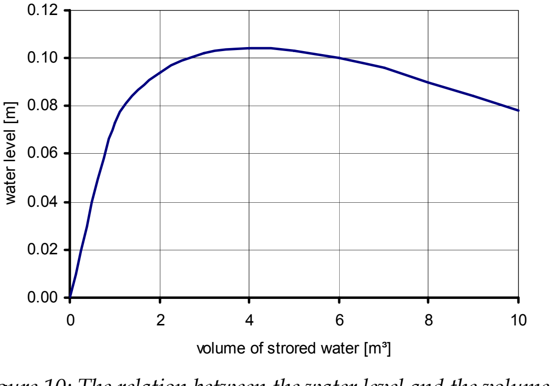


Figure 10: The relation between the water level and the volume of stored water

At that volume of stored water plastic deformations will occur, the stiffness of the structure will be reduced and finally the structure will collapse locally. From the results of this calculation it can be concluded that the "water raising capacity" of the structure is equal to 105 mm. The water level above the structure can not be higher than this value. The water raising capacity of a structure is the highest water level than can be achieved on the structure. When an iterative calculation is performed with a constant water level that is higher than the water raising capacity no equilibrium will be found.

4.3 Influence on water raising capacity

The characteristic behaviour of a structure during ponding can be described best by the graphs in which the water level and the volume of the stored water are given. In Figure 11 the influences of several variations on the behaviour of the structure, as given in Figure 7, are shown.

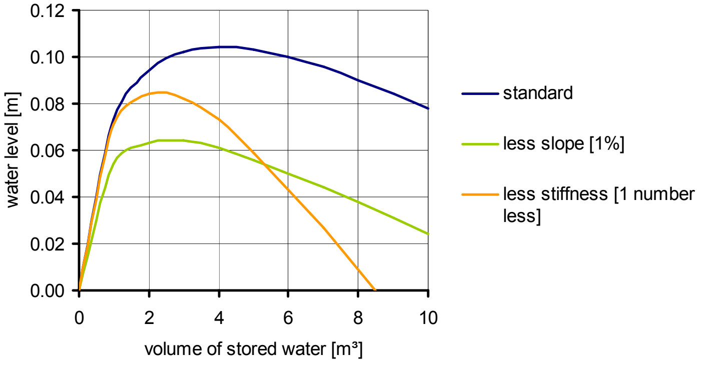


Figure 11: The relation between the water level and the volume of stored water for different situations

When the slope of the structure is less this will lead to a reduction of the water raising capacity. When the stiffness is less it can be seen that at first the behaviour is identical, but after a certain point the water level is much lower with the same amount of stored water. A reduction in stiffness also can lead to a reduction of the water raising capacity but more significant is that the slope of the second part of the graph is influenced by the stiffness.

For the graphs discussed in principle three basic forms can be distinguished, that are shown in Figure 12. In the curves a distinction can be made between two parts. The first part is determined by the slope of the structure. The stiffness of the structure has no significant influence on the behaviour in this part of the process. The second part of the curve is determined by the stiffness of the structure. If there is no slope in the structure, for which the relation between the water level and the volume of water is given by the dashed lines, only the second part of the graph lines remain for the relation between the water level and the volume of water.

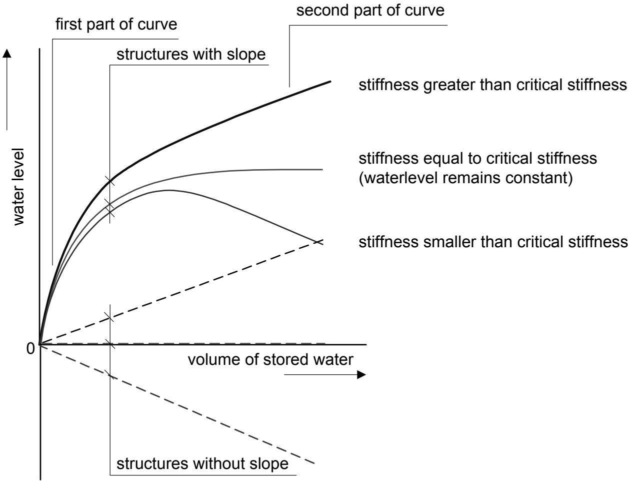


Figure 12: The relation between the water level and the volume of stored water for different stiffness

Blaauwendraad defines the critical stiffness (Blaauwendraad, 2005). When the stiffness of the structure is larger than the critical stiffness, the water level always increases with an increase of the volume stored water. When the stiffness of the structure equals the critical stiffness, the water level remains constant with an increase of the volume of stored water. And, finally, when the stiffness of the structure is smaller than the critical stiffness, the water level will decrease with an increase of the volume of stored water. Especially this last type of structures, with a stiffness smaller than the critical stiffness, are the structures that are vulnerable for ponding. For structures with a slope the decrease of the water level will appear after a certain water level is reached. For structures without a slope the decrease of the water level will start with the first storage of water.

From Figure 12 it can be concluded that the water raising capacity can be determined by two different criteria. At first, for structures of which the stiffness of the structures is less than or equal to the critical stiffness, the water raising capacity is determined by the slope and the stiffness of the structure only. The strength of the structure has no influence at all.

So in that situation the ratio between the stresses and the strength of the structure is no indication of the safety of the structure. Secondly for structures of which the stiffness is larger than the critical stiffness, the water raising capacity is determined by the slope, the stiffness and the strength of the structure. For these structures the ratio between the stresses and the strength is an indication for the safety of the structure.

4.4 *Frequency of structures with a stiffness smaller than the critical stiffness*

In Section 4.3 it is concluded that especially structures with stiffness smaller than the critical stiffness are vulnerable for ponding.[1] In this section the frequency of this kind of structures in the Netherlands is discussed. As stated in 3 the governing criteria for the structural design of the steel beams often is the required stiffness to fulfil the requirement that the additional displacement due to the variable load should be limited to 1/250 of the span. For a simple span this leads to the following requirement for the stiffness:

$$u_{ad} = \frac{5}{384}\frac{q_{ad}\, l^4}{EI} \leq \frac{l}{250}$$

so

$$EI_{u-ad} \geq \frac{1250}{384} q_{ad}\, l^3 \qquad (1)$$

For a characteristic value of the variable load q_{ad} = 0,50 kN/m², (1) can be rewritten to:

$$EI_{u-ad} \geq \frac{625}{384} a\, l^3 \qquad (2)$$

where:

EI_{u-ad} is the required stiffness in kNm² to fulfil the requirement for the additional displacement.

a is the centre-to-centre-distance between the steel beams in m.

l is the span of the beam in m.

[1] There is scientific discussion as to the importance of the critical stiffness. Structures with a stiffness larger than the critical stiffness have shown water accumulation problems and safe roof structures can be made with a stiffness less than the critical stiffness. Therefore, the analysis in this section has an approximate nature and is not applicable to individual situations. Instead of critical stiffness the water raising capacity seems to be a more objective measure for roof design.

By (*Blaauwendraad 2005*) the formula for the critical stiffness of a simple span is given:

$$EI_{cr} = \frac{\gamma a l^4}{\pi^4} \tag{3}$$

The variable γ is the weight of water, 10 kN/m³, so (3) can be rewritten:

$$EI_{cr} = \frac{10}{\pi^4} a l^4 \tag{4}$$

Where, EI_{cr} is the critical stiffness for ponding in kNm².[2] For several spans both EI_{u-ad} and EI_{cr} , both divided by the centre-to-centre-distance between the steel beams a, are given in Figure 13.

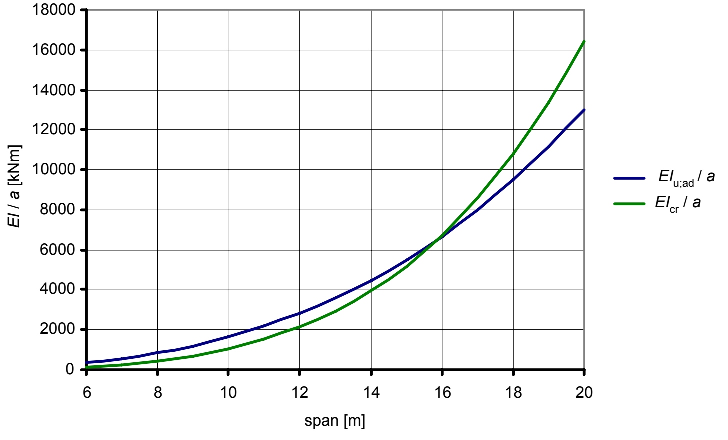


Figure 13: The relation the required stiffness for displacement requirements, the critical stiffness for ponding and the span by a simple span

[2] In (3) en (4) π^4 is used as denominator. In (Blaauwendraad, 2006) the denominator π^4 is replaced by 96.

From Figure 13 it can be derived that for simple span structures with a span smaller than 16 meter the required stiffness to fulfil the requirement for the additional displacement is larger than the critical stiffness for ponding. Those structures therefore are less vulnerable for ponding.
A similar comparison can be made for a two span beam. The essential difference for this situation is that while designing a two way span it may be assumed that the variable load is present on both spans, so:

$$u_{ad} = \frac{2}{384}\frac{q_{ad}\, l^4}{EI} \leq \frac{l}{250}$$

so

$$EI_{u-ad} \geq \frac{250}{384} a\, l^3 \tag{5}$$

However when ponding occurs in general this will only take place in one of the two spans. For this particular situation the formula for the critical stiffness is given in NPR 6703.

Table 2: Formula for critical stiffness (NPR 6703, 2006)

scheme		critical stiffness
	$C = 0$	$EI_{cr} = \frac{\gamma_{rep} a\, l^4}{\pi^4}$
	$C = \frac{3\, EI_{cr}}{l}$	$EI_{cr} = \frac{7}{10}\frac{\gamma_{rep} a\, l^4}{\pi^4}$
	$C = \infty$	$EI_{cr} = \frac{2}{5}\frac{\gamma_{rep} a\, l^4}{\pi^4}$
	$C = \frac{3\, EI_{cr}}{2l}$	$EI_{cr} = \frac{2}{5}\frac{\gamma_{rep} a\, l^4}{\pi^4}$
	$C = \infty$	$EI_{cr} = \frac{1}{5}\frac{\gamma_{rep} a\, l^4}{\pi^4}$

The formula for the critical stiffness in this situation can be rewritten to:

$$EI_{cr} = \frac{1}{10}\frac{\gamma a l^4}{\pi^4} = \frac{7}{\pi^4} a\, l^4 \tag{6}$$

The comparison between the two requirements for the stiffness is given in Figure 14.

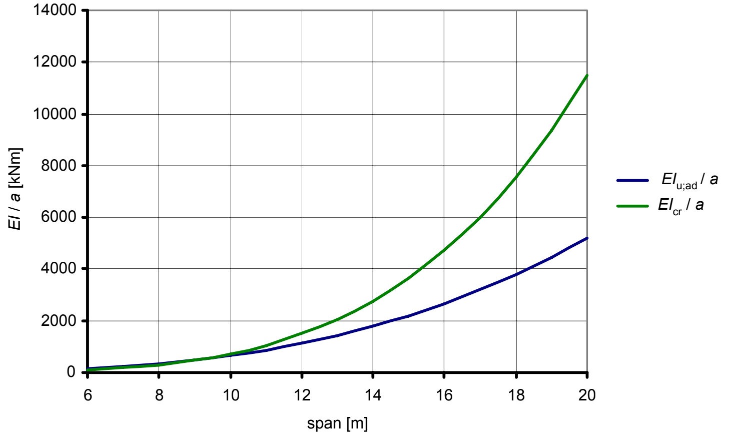


Figure 14: The relation the required stiffness for displacement requirements, the critical stiffness for ponding and the span by a two span beam

From Figure 14 it can be concluded that for a two span structure with a span larger than 9 meter the required stiffness to fulfil the requirement for the additional displacement is smaller than the critical stiffness for ponding. These kinds of structures often have a span larger than 9 meter. Spans of 15 to 20 meter are most common. Structures with two span beams or other continuous beams, with common spans of 15 meter therefore most of the times have a stiffness that is smaller than the critical stiffness with respect to ponding. Therefore, these structures in general are vulnerable for ponding.

5 What to do to prevent collapse due to ponding?

To prevent local collapse due to ponding on the roof an emergency drain system should be provided. The water level required to make this system work properly should be smaller than the water raising capacity of the structure. An emergency drain system is a system that has a free outlet, the outlet should not be connected to the sewer system. Also the gullies or overflows of the emergency drain system should be detailed in a way that leaves and feathers will not block the system. According to NEN 6702 these emergency drain systems should be designed for a rain intensity of 14 mm/ 5 minutes, see Table 1.

Often an emergency drain system is provided with a threshold to prevent the system to work immediately. The sum of the threshold en the water depth required to achieve sufficient drainage should be smaller than the water raising capacity of the roof structure. In the design the water raising capacity of the structure can be increased by increasing the slope or the stiffness of the structure.

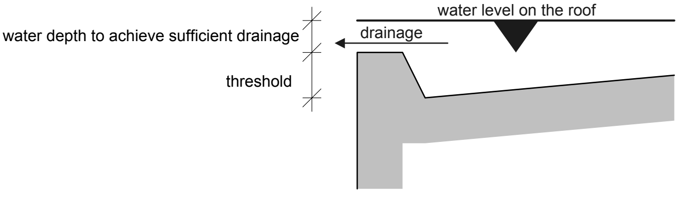


Figure 15: Overflow of emergency drainage system

6 Reasons for a great amount of damages

As can be derived from (*Kool, 2003*) a great amount of local collapses due to ponding has occurred in the Netherlands. The reasons for this are several. Until 1992 the load caused by rainwater and the behaviour of structures loaded by water were not defined in the structural codes. So structural engineers did not consider this load in the design and also emergency drainage systems were often not used. In 1992 the first edition of NEN 6702 became available. In this code the load caused by rainwater is described. In the code it is stated that the structural engineer has to assume a total malfunction of the regular rainwater drainage system and has to design a sufficient emergency drain system.
Experience with the analyses of several cases that were designed after 1992 leads to the conclusion that although the load caused by rainwater is described in the code, structural engineers often did not consider the load due to water storage in their design. The design of the emergency system, if it was present, was based on rules of thumb instead of structural calculations. This has lead to situations where an emergency drain was available with a threshold that was higher than the water raising capacity of the structure. So, when the regular system was blocked during a thunderstorm a collapse of the roof occurred without the emergency system being activated.
By the publication of the NPR 6703 it is tried to make the design of light weight structures for ponding easier for the designer. In the NPR 6703 some empirical formulas for the water

raising capacity of light weight structures are given. These empirical formulas are presented in Blaauwendraad (2007).

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