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Failures of suspended ceilings and execution errors

Awarie sufitów podwieszanych i błędy wykonawcze

Abstract

When observing the stability of suspended ceilings during operation, sometimes smaller failures are observed, up to disasters, even a few of considerable sizes and serious consequences. The aim of the article is to analyse the causes of damage to a suspended ceiling, with an area of approximately 500 m^2, as well as testing and checking the applied construction elements. In situ destructive tests as well as tests at the AGH laboratory were carried out. The analyses were carried out in accordance with PN/EN 13964: 2014 (E). It was found that the designed ceiling system solution was correct. Whereas in the performance, an improper spacing of hangers, even by more than 70% of the permissible spacing, and forbidden lengths of brackets from C60 profiles, were applied. Also, about 55% of the connectors had too small diameters of the ends of the mandrels, which allowed for the sliding of broken head and a sudden loss of carrying capacity of the hanger.

Keywords: failures, suspended ceilings, metal expansion anchors

Streszczenie

Obserwując stateczność sufitów podwieszanych w czasie eksploatacji, zauważa się występowanie mniejszych awarii, aż do katastrof – kilku o znacznych rozmiarach i poważnych konsekwencjach. Celem artykułu jest analiza przyczyn uszkodzeń systemowego sufitu podwieszanego, o powierzchni około 500 m^2 oraz badania sprawdzające zastosowanych elementów konstrukcyjnych. Wykonano badania niszczące in situ oraz w laboratorium AGH. Analizy przeprowadzono zgodnie z PN/EN 13964:2014 (E). Stwierdzono, że zaprojektowane rozwiązanie systemowe sufitu było prawidłowe. Natomiast w wykonawstwie zastosowano, m.in. niewłaściwe rozstawy wieszaków, nawet o ponad 70% większe, niż dopuszczalne oraz niedozwolone długości wsporników z profili C60. Również około 55% łączników posiadało zbyt małe średnice zakończeń trzpieni, które umożliwiały przeciśnięcie zerwanej główki i nagłą utratę nośności wieszaka.

Słowa kluczowe: awarie, sufity podwieszane, metalowe kotwy rozporowe

1. Introduction

Currently, suspended ceilings constitute a standard element of interior finishing in many buildings. In addition to architectural and aesthetic values, they make it possible to separate the space to place various installations, which are very extensive in new buildings. System solutions for suspended ceilings, utilising complete, ready-made elements for assembly during the construction works, in line with the required work method, are typically used. Bespoke solutions, which make it possible to meet atypical criteria, are used more rarely.

When observing the in-service stability of suspended ceilings, one can note the occurrence of minor failures as well as collapses, some of them being of extensive proportions and having serious consequences. It is important to identify the causes and mechanisms of such failures.

Naturally, the system assumptions strictly define the scope of and limitations in the application of the intended solutions, the rules for the preparation of materials and construction, as well as methods of operation. All these conditions must be met unconditionally, since they were assumed at the design stage of the system. The results of testing of a suspended ceiling with an area of 500 m^2, a central fragment of which, with an area of 30 m^2, failed. After a lowering of approx. 10 cm was noticed, the ceiling was supported from underneath and repaired.

In situ tests of breaking loads on expansion anchors and laboratory tests of the applied hangers were conducted. The tests of the system elements were conducted in the laboratory of the Department of Geomechanics, Civil Engineering and Geotechnics, AGH, while the admissible loads were tested in line with PN/EN 13964:2014 [5].

Progressive collapse is the most dangerous, as it leads to the complete destruction of the structure in a short time. Such a mechanism was at work in many cases of collapse. The article analyses the mechanical condition of a suspended ceiling as a multi-hanger suspended structure undergoing gradual and progressive degradation. The process of tension redistribution, leading to the successive elimination of hangers in the ceiling's structural system, was investigated. The conducted analyses of the collapses and results of simulations involving model suspended ceilings made it possible to suggest a method of reducing the risk of progressive collapse through the application of additional hangers – safety devices – directing the process of structural failure.

2. Failures and collapses of suspended ceilings

Nowadays, suspended ceilings are practically a standard finishing element in public buildings (shopping malls, restaurants, railway/bus stations, auditoriums, halls, etc.). The observation of civil engineering incidents in such buildings has shown that failures or collapses of suspended ceilings are not rare, and may result in fatalities [1]. In mechanical terms, a suspended ceiling is usually a steel multi-hanger scaffold structure fixed to the floor slab. The bottom of the steel scaffold is usually closed by the gypsum board. Such a structure often weighs about 30 kilograms per one square metre, and sometimes much more. Clearly,

in the case of a collapse of a ceiling with an area of several dozen to several hundred square metres, the falling structure can weigh up to a dozen or so tonnes, becoming a threat to the life and health of many people.

Construction failures of suspended ceilings usually involve damages (cracks, fractures, excessive bending) or displacements of whole structures or their fragments. These damages should prompt measures aimed not only at their removal, but also at the identification of their causes, with a view to preventing further damage and a potential collapse. If the symptoms appear early, which is a favourable situation, preventive measures can be taken in advance. Unfortunately, large-scale collapses are rarely preceded by symptoms foreshadowing a real threat.

A construction collapse of a suspended ceiling means an unintended, sudden destruction of the entirety or significant portion of its structure. Unfortunately, one of the characteristic properties of suspended structures is their high sensitivity to progressive collapse over a short period of time (from several to several dozen seconds). An impulse which disengages one or several hangers as a result of the redistribution of forces leads to the breakage of subsequent elements. This triggers an extremely dangerous progressive destruction mechanism, causing the entire structure to collapse. The causes of this impulse, i.e. of the disengagement of first hangers, vary and are associated with design errors, use of faulty elements, construction errors and inappropriate use and maintenance. Often, the collapse has several causes, prompting a search for the primary cause. The scale of destruction can sometimes be extensive, covering areas exceeding 1,000 square metres of ceiling [1]. The weight of the falling structure can reach several dozen tonnes, which is why some collapses result in fatalities.

In 2010, during the construction of a sports hall in the Public School Complex No. 3 in Wadowice, the suspended ceiling over the entire area of the hall collapsed (approx. 1,000 m^2). The progressive nature of this collapse led to the destruction, in a short period of time, of the entire erected structure – Figure 1. Several people sustained injuries.

Fig. 1. The collapse of the suspended ceiling in the sports hall in Wadowice, 2010

In 2014, approximately 800 m^2 of a suspended ceiling collapsed in a shopping mall in Poznań. Luckily, this collapse took place at night and caused no casualties. Hangers being overburdened with catwalks and the disconnection of some of the hangers for the duration of works were suggested as the primary causes. The secondary cause, leading directly to the triggering of the failure mechanism, was the excessive load on the ceiling by water seeping out of a damaged fire sprinkler system, found by an expert to have been a random cause.

In 2017 in Białystok, a suspended ceiling, with an area of approx. 350 m^2, collapsed during a fire in a building rented by a wholesale store. The impulse which triggered the collapse was two firemen stepping onto the ceiling structure (local hanger overload). The firemen died as a result of falling from more than 4 metres. The collapse developed in a progressive manner, with an additional possible cause being the rapidly rising temperature in the building on fire.

In January 2018, a suspended ceiling collapsed in the renovated Varketili metro station in Tbilisi, injuring 14 people. The collapse quickly affected a substantial portion of the structure, developing in a way which is characteristic of progressive collapse.

Failures and collapses of suspended ceilings can be observed rather often and commonly. Many construction incidents which, luckily, do not result in any casualties are not reported by the media. The presented examples indicate a similar nature of the origin and development of the collapse mechanism. Usually, it leads to the destruction of the entire structure, which collapses in a short period of time. In this context, a question arises whether suspended ceiling structures must be so commonly exposed to the risk of progressive collapse, for which a local impulse causes degradation to develop on a wide scale. It appears advisable to take measures modifying commonly used structures in such a way that the progressive collapse triggered by an impulse be locally limited.

3. The subject and scope of tests

Suspended ceilings in two identical restaurant rooms in Kraków, with an area of approx. 500 m^2 each, with shapes resembling rectangles, were subjected to testing.

"After noticing a substantial bend in the ceiling edge, which was already approx. 10 cm in the centre, the lowered section was propped and the damage was repaired. Next, testing was commissioned and additional security measures were taken".

In accordance with as-built documentation, the analysed ceiling was built according to a Knauf system, based on a metal structure [2–4], with gypsum board decking 2 * 12.5 mm. Between the reinforced concrete slab and suspended ceiling, there are many, densely laid system pipes with various sections, from a dozen or so cm2 to more than 1 m^2. Light access panels are fixed in openings in the decking, in irregularly spaced locations, as well as air-conditioning units, ventilation boards, lighting lamps and sprinklers. The densely placed installations and equipment hindered the positioning of hanger axes in straight lines.

The destructive tests for the pull-out resistance of expansion anchors were conducted in situ in the facility and in the laboratory of the Department of Geomechanics, Civil Engineering and Geotechnics, AGH. In addition, breakage tests of the individual elements of the hangers were performed in the laboratory.

4. Erification sizing of the ceiling according to the system applied and the actual spaces between hangers

In the Knauf system, NIDA WGN 20 system, in respect of "Verification sizing of the ceiling", point 4. Determining the basic geometric parameters, the axial distances of: hangers – a, main runners – c, and support tracks – b, is provided for, in line with Figure 2 and Table 1.

In line with the Knuf system, hangers with a load capacity of 0.30 kN, and – as indicated in Table 1 – axial distances c = 110 cm and a = 75 cm, should have been applied.

On the basis of a survey, it was found that main runner hangers in the failure area were present with the most unfavourable axial spacing of main runners c_{Imax} = 105 cm and a_{Imax} = 130 cm. The values permissible according to the Knauf system were exceeded significantly. Furthermore, other errors were observed. Due to the location of an access panel, the main runner was not continuous (one cantilever was 120 cm long and the other was 15 cm long). Some hangers were tensioned and subjected to significant loads, some were less tensioned, and a few were completely loose (this could have been caused by rectification of the floor slab level only in respect of selected hangers, with the adjacent ones remaining unadjusted). A small number of hangers were fixed with an approx. 15% tilt from the vertical due to conflicts with installation routes.

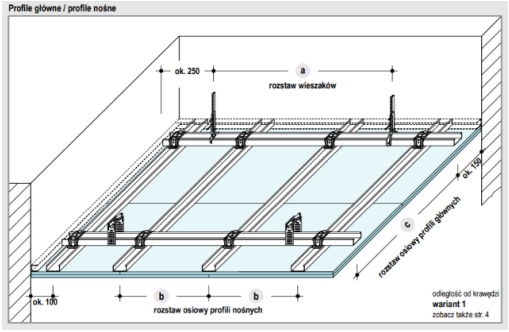

Fig. 2. Geometric parameters according to Knauf NIDA WGN 20

Table 1. According to Knauf, NIDA WGN 20

Maksymalne rozstawy
• z odpornością ogniową od dołu • bez odporności ogniowej wszystkie wymiary w mm

Rozstaw osiowy c profili głównych	Rozstaw wieszaków a klasa obciążeń kN/m2 (zobacz strona 2)			Tylko sufit pod sufitem
	do 0,15	do 0,30	do 0,50 1)	do 0,65 1)
500	1200	950	800	750
600	1150	900	750	700
700	1100	850	700	650
800	1050	800	700	-
900	1000	800	-	-
1000	950	750	-	-
1100	900	750	-	-
1200	900	-	-	-

1) Stosować wieszaki o klasie nośności 0,40kN

5. Admissible loads based on destructive tests

The PN/EN 13964:2014 (E) suspended ceilings – Requirements and test methods standard [5] "covers membranes, individual substructure components, substructure kits and suspended ceiling kits intended to be placed on the market". In accordance with this standard, the admissible hanger load (adm$F$) in kN equals:

$$\text{adm } F = F_u^{5\%} / v, \tag{1}$$

$$F_u^{5\%} = F_u - k_\sigma \cdot s \tag{2}$$

where:

$F_u^{5\%}$ – unfactored load, 5% quantile, kN,
v – safety factor, $v = 2.5$,
F_u – average breaking load, kN,
k_σ – statistical factor,
s – standard deviation.

Depending on the number of n – tests in a given sample, the values of k_σ factors are determined as per Table 2 in the referenced standard [5].

Table 2. Acceptance factor k_σ [5]

Fractile ϕ	**$v = n - 1$**												
	Number of test specimens												
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
$W = 90$ 5%	5.31	3.96	3.40	3.09	2.89	2.75	2.65	2.57	2.50	2.45	2.40	2.36	2.33
NOTE 1 Values for k_σ depending on the number of test samples n, the probability (W) and the fractile value ϕ (assumption – the standard deviation is unknown). NOTE 2 For this standard, the probability W and the fractile value ϕ have been fixed at 0,90 and 5%, respectively. For $n = 10$ lest pieces, the prevailing k_σ value is 2,57.													

5.1. In situ destructive tests for the pull-out resistance of expansion anchors

The direct cause of the failure of the suspended ceiling in question was the breakage of the heads of KSMM metal expansion anchors, Figures 3a and 3b. Therefore, the in situ tests covered the expansion anchors.

Each NIDA WGN 20 hanger, fixed to the floor slab using one KSMM anchor, was subjected to an increasing force until breaking the connection with the floor. During tests of 11 specimens of the installed KSMM metal expansion anchors, distributed evenly on the entire area of the room, in one case the entire anchor was pulled out of the floor when subjected to a force of 2.29 kN. In six cases, the head of the KSMM expansion anchor broke. In three cases the breakage of the anchor head was observed first, and when greater force was applied, the pins were extracted from the torn anchor wedges together with the head, and

finally, all parts, including the wedges, were extracted from concrete, Figure 3c. Furthermore, tests similar to those described above were conducted in situ, with the application of two anchors fixing each nonius top hanger to the ceiling.

Similar in situ tests for the extraction of anchors were performed on the ceiling from the second restaurant, installed by a different Company 2. In these tests, it was observed in each case that first, the head was torn off; next, the pins were extracted with the head; and finally, all other anchor elements were extracted from concrete, including the torn-off wedges.

The results of tests and calculations, in line with the presented assessment of admissible loads in the individual destructive tests, as per reports (1.1) and (1.2), are listed in Table 2.

KSMM metal expansion anchors with nonius top hangers engaged in a chain design in each case meet the required admissible hanger load requirements for the Knauf system, adm$F \geq 0.3$ kN.

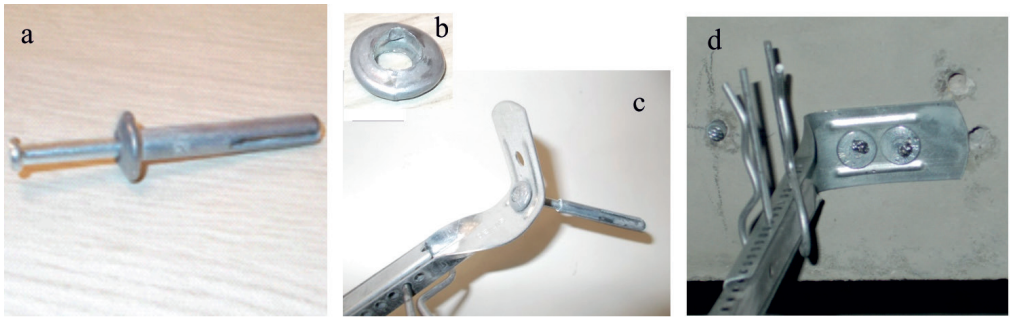

Fig. 3. KSMM metal expansion anchor – a and after the load destructive testing, a – torn off head, b – torn off head with extracted wedge on the pin, d – top hanger fixed with two ZSP expansion anchors, in violation of the approval

It is worth noting that KSMM anchors, installed by Company 1, are characterised by similar breaking loads for head breakage of 1.31 kN and 1.32 kN, respectively, for the breakage of the head only (in approx. 55% of anchors) and for head breakage followed by the extraction of the elements of expansion anchors (in approx. 45% of anchors).

Table 3. The results of breaking load tests and the calculated unfactored values of the applied suspended ceiling kits according to the Knauf system, following the chain design – KSMM metal expansion anchor and nonius top hanger

Company	Description	F_u kN	s	$F_u^{5\%}$ kN	adm$F$ kN
1	Expansion anchor head breakage	1.31	0.16	0.82	0.33
	Head breakage / expansion anchor extraction	1.32 / 2.89	0.12 / 0.37	0.83	0.33
	2 expansion anchors applied	2.34	0.37	0.87	0.35
2	Head breakage / expansion anchor extraction	1.81 / 2.72	0.23 / 0.79	1.03	0.41

F_u – average breaking load, s – standard deviation, $F_u^{5\%}$ – unfactored value, 5%, adm$F$ – admissible hanger load

The breakage of anchor heads only, which was the case in 55% of all hangers fixed by Company 1, suggests a production error. This is indicated by pin end parts, which had smaller diameters than the openings in the torn off heads, which allowed their sliding off the pins. In the remaining cases, the broken head caused the subsequent extraction of the pin, followed by the extraction of the entire external wedge of the anchor – see Figure 3.

When the pin is extracted along with the broken head, the structure is much safer, as after the head is broken by a smaller force, it is followed by the extraction of the pin from the wedge by a force which is, on average, 2.2 times greater, and an evident displacement (lowering) of the hanger, by approx. 2 cm, is observed. Sudden, complete loss of load capacity takes place afterwards, i.e. in the last phase when the broken head, pin and broken wedge are extracted from concrete. Such a sudden loss of load capacity occurs immediately when the heads alone are torn off, on average with a force more than two times lower.

The installed hangers, each on two anchors, Figure 4a, were characterised by an average breaking load of 2.34 kN, which was by 19% and 14% smaller than the breaking loads for single anchors in the case of their extraction with heads, fixed by Company 1 and Company 2, respectively. Therefore, the application of two anchors instead of one correctly installed anchor, does not result in an increase in the average breaking load (at the same time, in accordance with Technical Approval ITB AT-15-7305/2014 Metal expansion anchors, [2], the application of anchors with spacing smaller than 12 cm is forbidden).

When comparing average breaking loads F_u (breakage of anchor heads), it can be noted that anchors installed by Company 1 were characterised by breaking loads by 27% smaller than those for anchors installed by Company 2. The significant discrepancy between these loads, by more than ¼, can stems from differences in the load capacity of anchors made by different producers.

5.2. Laboratory destructive tests for the applied suspended ceiling elements

Six cycles of breaking load tests for the applied elements of the suspended ceiling were conducted in the laboratory of the Department of Geomechanics, Civil Engineering and Geotechnics, utilising Veb Werkstoffprufmaschinen Leipzig press No. 28218 13/6062. The results of the tests and calculations as per (1) and (2) are presented in Table 3.

The results of calculations for each test cycle confirm that the condition of admissible hanger load adm$F$ > 0.3 kN was met.

The weakest link in the entire chain design – metal expansion anchor and the individual elements of the ceiling structure – was the connection of bottom hanger and CD 60 profile (F_u = 0.977 kN), Figure 4a. In the suspended ceiling which had failed, every connection of bottom hanger and CD 60 profile was additionally reinforced by two 3.5*25 screws, Figure 4b. This solution was characterised by an average breaking load of F_u = 2.00 kN. Greater average breaking loads, in order from smallest to greatest, characterised bottom hanger rivets (F_u = 2.54 kN), ZSP anchor heads (F_u = 3.10 kN; Figure 4c) and KSMM anchor heads (F_u = 3.24 kN).

Table 4. The results of breaking load tests conducted in the laboratory and the calculated unfactored values of the suspended ceiling elements, following the chain design – metal expansion anchor and nonius top hanger, and the individual elements of the system

Description	F_u kN	s	$F_u^{5\%}$ kN	adm$F$ kN
KSMM metal expansion anchor and hanger elements including CD 60 profile (connection breakage: bottom hanger – CD 60 profile, Fig.)	0.977	0.025	0.844	0.338
KSMM metal expansion anchor and hanger elements including CD 60 profile; bottom hanger fixed with two 3.5*25 screws (connection breakage bottom hanger – CD 60 profile, installed as above)	2.00	0.22	0.83	0.33
KSMM metal expansion anchor and hanger elements (bottom hanger rivet breakage)	2.54	0.287	1.02	0.406
KSMM metal expansion anchor and nonius top hanger (KSMM anchor head breakage)	3.24	0.29	1.70	0.68
ZSP metal expansion anchor and nonius top hanger (ZSP anchor head breakage)	3.10	0.34	1.77	0.71
F_u – average breaking load, s – standard deviation, $F_u^{5\%}$ – unfactored value, 5%, adm$F$ – admissible hanger load				

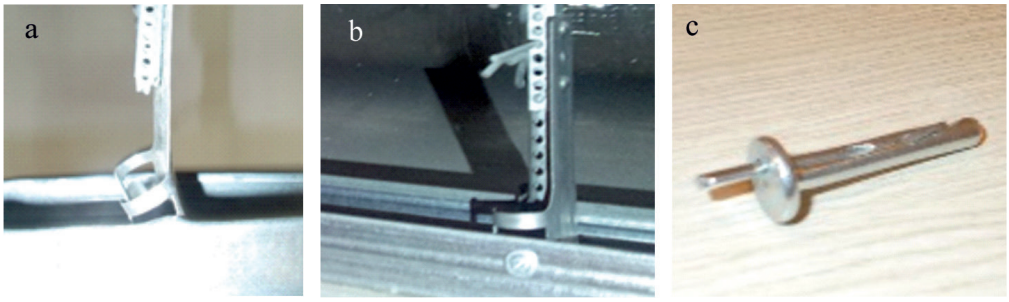

Fig. 4. Deformation of connection of bottom hanger and CD 60 profile – a, additional bonding of elements with two 3.5*25 screws – b, ZSP metal expansion anchor – c

6. Conclusion

The extensive application of suspended ceilings, as well as their failures and collapses involving a sudden drop of entire ceiling planes, which can span as much as several hundred square meters, prompts extended tests which would facilitate more accurate identification of the causes and reduction of the risk of collapse.

The preliminary tests of two identical suspended ceiling systems with 2*12.5 mm gypsum board decking, with an area of approx. 500 m2 each, performed by different companies revealed, the following:

- non-conformances in terms of construction (Company 1)

- exceeding the maximum distances between hangers, by as much as 73%, and the lack of continuity of the main runner, which resulted in cantilever with a length of 115 cm against 20 cm provided for in the system,
- non-vertical setting of a dozen or so hangers (where the density of building installations was denser; 15° tilt from the vertical),

- non-conformances in the manufactured materials
  - about 55% of the expansion anchors installed in the ceiling, a part of which has failed, indicated a production error, since the end parts of pins had smaller diameters than the openings in the torn-off heads, which made it possible not to extract the pin with greater force after the head was torn off, and thus resulted in decreased load capacity of the entire anchor.

Based on destructive tests, the following was determined:

- a significant discrepancy between average breaking loads in situ to extract metal expansion anchors, exceeding ¼, which resulted from a low load capacity of the anchors used by Company 1.
- faulty assembly of the hangers, each on two anchors, does not lead to average breaking loads being higher than in the case of a single anchor,
- KSMM anchors (F_u = 3.24 kN) were characterised by greater average breaking loads than ZSP anchors (F_u = 3.10 kN); furthermore, in the case of KSMM anchors, first, the anchor head is broken with a lower force, next the pin is extracted from the anchor wedge on average with even two times greater force with simultaneous displacement of the hanger by approx. 2 cm, and finally we can observe a sudden and complete loss of load capacity.
- non-systemic application of additional bonding of the bottom hanger and CD 60 profile, using two 3.5*25 screws, results in the average load capacity of the connection being approx. two times greater.

The results were obtained on a small sample, which is why they may not be generalised.

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