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Study on the load bearing capacity and the load-deferral behavior of wooden composite beams with a teethed joint

Badanie nośności i pracy w warunkach obciążenia fazowego drewnianych belek kompozytowych z połączeniami zębatymi

Key words: teethed joint, load bearing capacity, shifting modulus, historical timber structures

Słowa kluczowe: połączenie zębate, nośność elementu, moduł podatności, drewniane obiekty zabytkowe

1. TEETHED BEAMS

A „teethed beam“ is a composite beam which consist of multiple wooden components. The special feature of these beams is that the individual components are joined together with a sawtooth-like connection [1], [2]. Ancient roman illustrations of wooden bridges are a proof of the application of such composite beams. They have been used until the late 19th century to realize large span widths with heavy loads – e.g. in ceiling constructions of town halls and churches or in bridges and roof constructions.

The composite beams are typically consisting of three components – a continuous element on the bottom and two mid-jointed parts on top (see fig. 1).

The development of novel connections and fasteners since the mid-19th century – e.g. hardwood dowels, clamps, drift bolts and specifically designed dowels – gradually replaced the teethed beams. The invention of the glued laminated timber (see also [5], [6], [7], [8])

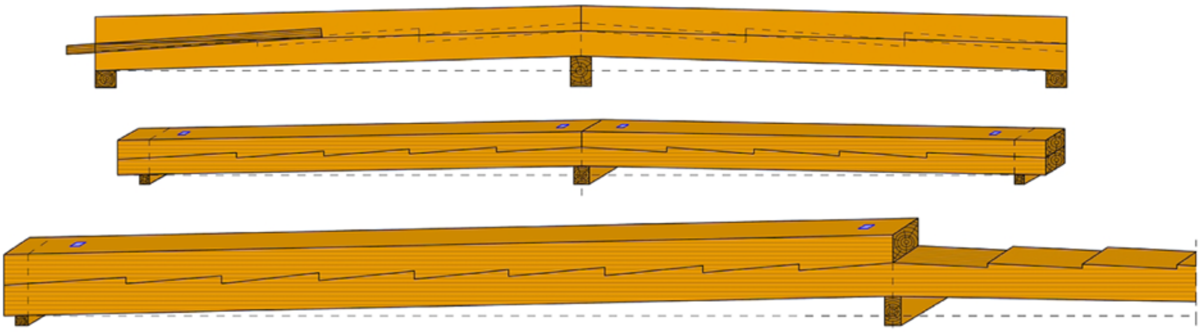

Fig. 1. Shematic depiction of a teethed beam according to informations from 1764 (for a span width of 8,5–22 m, taken from [4])

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Cytowanie / Citation: Rug W., Linke G. Study on the load bearing capacity and the load-deferral behavior of wooden composite beams with a teethed joint. Wiadomosci Konserwatorskie – Journal of Heritage Conservation 2016;46:109-116

Otrzymano / Received: 05.11.2015 • Zaakceptowano / Accepted: 26.11.2015 **doi:10.17425/WK45COMPOSITE**

Praca dopuszczona do druku po recenzjach *Article accepted for publishing after reviews*

and the associated opportunity of producing arbitrarily large cross-sections made the complicated production of teethed beams unnessecary.

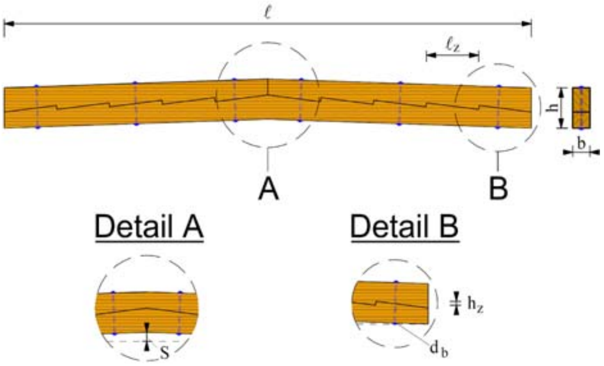

Fig. 2. Constructive details of a teethed beam

The constructive regulations and recommandations concerning the teethed beams which can be found in the literature are only slightly differing. The depth of the teeth h_z is mostly determined as $1/10^{th}$ of the beam's height. The length of the teeth l_z equals the composite beams's height. The tooth joint is designed so that the shear forces are transferred over the frontal faces of the teeth. The orientation of the teeth alternates in the middle of the beam [3], [4] (see fig. 2). Furthermore, the teethed beams have been produced with a camber of $s = l/60$ (until 1900) to $s = l/200$ (until 1950). The camber assures the form fit and force transfer.

The tooth joint is a ductile connection between the individual components. In the past, this was taken into account by reducing the section modulus respectively the permissible flexural strength.

MÖHLER (1912–1993) developed in the 1950s the so called γ-method which allows the calculation of flexural members consisting of ductile connected components. This method was primarily regulated normative in the 1969 published version of the DIN 1052.

2. STUDIES ON THE LOAD BEARING CAPACITY OF TEETHED BEAMS

The starting point of these studies was the reconstruction of the roof construction of a 270 years old church tower. In this roof construction, the multiple layers of the timber beam floor were suspended from five wooden upstand beams (wood species: pine). These wooden upstand beams were executed as teethed beams (see fig. 3, left).

Two of the five upstand beams were damaged on the supports due to biotical harmful organisms. These damaged beams should be replaced with new, true to original reproduced teethed beams (see fig. 3, right).

The replacement of the damaged beams was readily possible since the original beams have fulfilled their static function beyond doubt. Therefore, static calculations were not required according to the regulations of the back then valid DIN 1052:2008, paragraph 4(3).

The renunciation of static calculations required a particular accuracy in the preparation of the new construction members as well as on their monitoring to ensure the same load bearing capacity without any ductility due to slippage. This was especially necessary concerning the teethed joints.

The replacement of the upstand beams led to the question of the actual load bearing capacity of the teethed beams. Therefore, in 2010 studies on the load

Fig. 3. Left: 270 years old teethed beams as upstand beams; right: true to original reproduced teethed beam (wood species: pine)

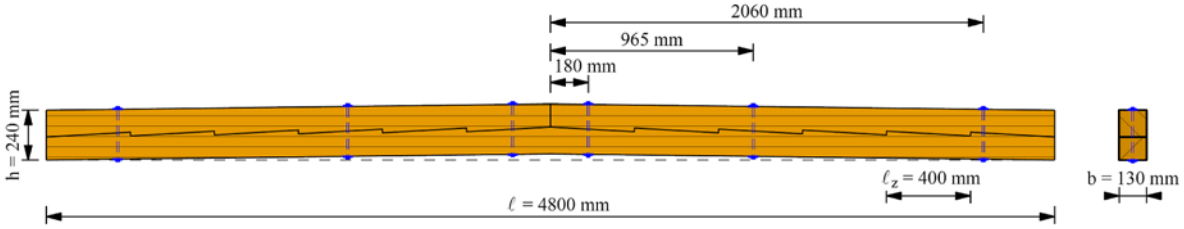

Fig. 4. Specimen (scale 1:2) for the determination of the flexural load bearing capacity

bearing capacity and the load deferral behavior of teethed beams took place at the University of sustainable Development, Eberswalde.

Subject of the studies were three scaled down model beams (scale 1:2) of the replaced upstand beams (see fig. 4).

The load bearing capacity and the load-deferral behavior of the tooth joint were determined in shear tests on 12 specimen on a scale of 1:1 (see fig. 5) as well as on 3 specimen on a scale of 1:2.

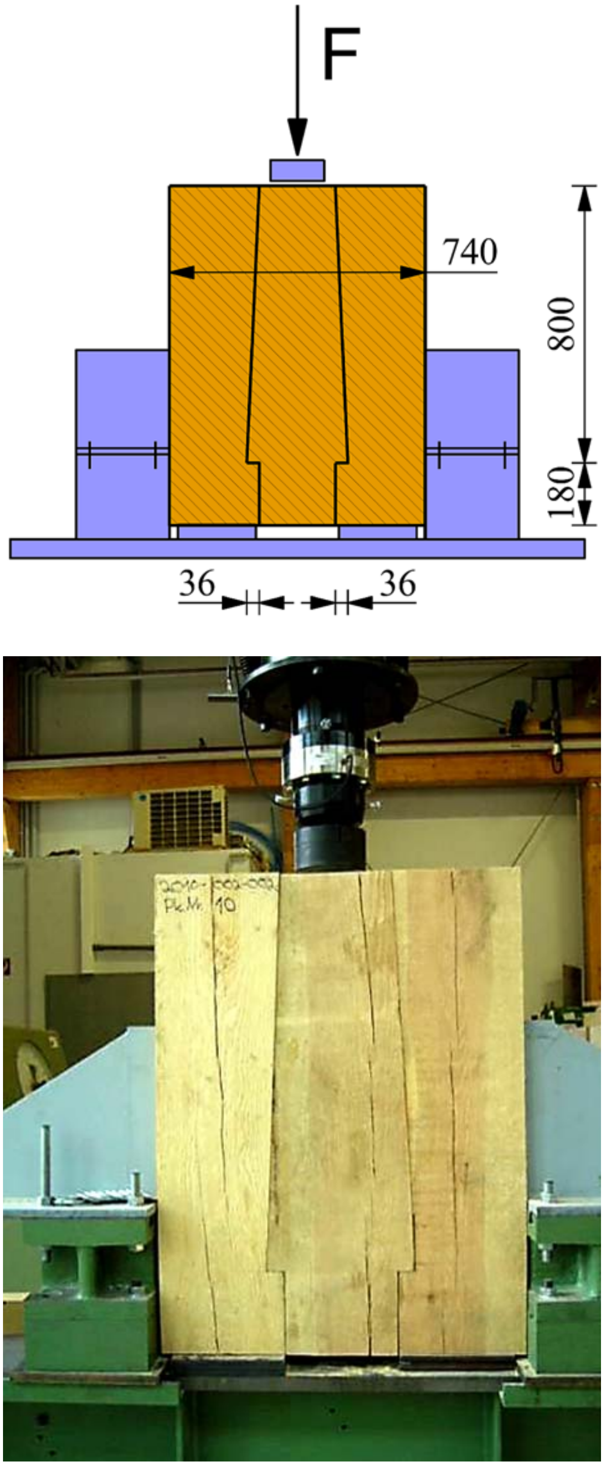

Fig. 5. Specimen (scale 1:1) for the determination of the load bearing capacity and the load-deferral behavior

2.1. Studies on the load bearing capacity and the load – deferral behavior of teethed joints

The modulus of displacement K_{ser} of the teethed joint is a substantial requirement for static calculations of teethed beams with the calculation method according to EN 1995–1-1, appendix B.

The EN 1995–1-1 allows only the calcultation of modulus of displacement of dowel-type fasteners or specifically designed dowels. Therefore, the modulus of displacement of the tooth joint had to be determined in experimental studies according to the EN 26891.

Subject of the experimental studies were three-part specimen with a tooth joint on both sides (see fig. 5).

2.1.1. Experimental procedure

Prior to the experimental studies the estimated maximum load F_{est} has to be determined by calculation or preliminary tests. This estimated load is used as a reference value for the load application procedure respectively the load application speed. In this case the estimated maximum load of $F_{est} \approx 525$ kN was determined in preliminary tests.

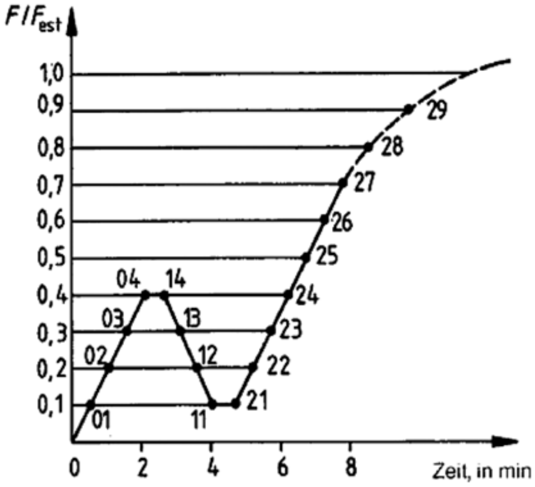

Fig. 6. Load application procedure according to EN 26891, picture 1

The load application procedure is divided in five phases (see fig. 6):

Phase 1: The applied test load equals 40% of the estimated maximum load ($0,4F_{est}$). This load has to be applied continuously within 120 seconds.

Phase 2: The test load of $0,4F_{est}$ is kept constant for 30 seconds.

Phase 3: The test load is reduced to 10% of the estimated maximum load ($0,1F_{est}$) within 90 seconds.

Phase 4: The test load of $0,1F_{est}$ is kept constant for 30 seconds.

Phase 5: The test load is increased continuously until the failure of the specimen. The end of the test is determined as a fraction (the test load is decreased by 50%) or a displacement of 15 mm is reached.

2.1.2. Results of the shear tests

The shear tests in a scale of 1:1 according to EN 26891 have provided the following results (see also fig. 7 and table 1):

1. The average modulus of displacement of a specimen with two tooth joints is $K_{ser,mean}$ = 35716 N/mm;
2. The mean value of the density of all twelve specimen is $\rho_{u,mean}$ = 593.45 kg/m^3;
3. The characteristic density of all twelve specimen is ρ_k = 469.28 kg/m^3.

Table 1. Statistical results of the shear test in a scale of 1:1

shear test on specimen in a scale of 1:1	K_{ser} according EN 26891 [N/mm]	$\rho_{u,mean}$ according EN 384 [kg/m^3]
quantity of specimen	12	12
mean value	35716.30	593.45
minimum	33591.66	428.84
maximum	39580.08	767.22
standard deviation	2021.97	75.26
coefficient of variation	0.06	0.13

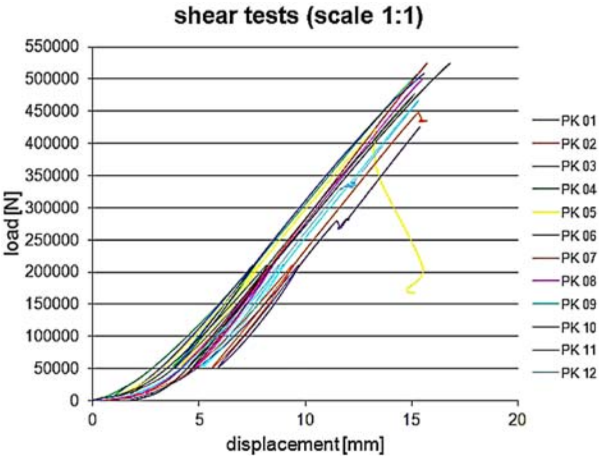

Fig. 7. Load-deformation curve, shear test in a scale of 1:1

Eleven of the twelfe specimen reached a displacement of 15 mm. The specimen No. 5 showed a shear fraction on one tooth joint (see fig. 8). Next to the fraction a relatively large amount of sapwood could be determined. Despite this fact, the specimen also showed a high modulus of displacement. Therefore, the results of this test remained in the further statistical analysis.

Fig. 8. Shear fraction on a tooth joint – specimen No. 5 (scale 1:1)

The shear tests in a scale of 1:2 according to EN 26891 have provided the following results (see also Table 2):

1. The average modulus of displacement of a specimen with two tooth joints is $K_{ser,mean}$ = 29333.33 N/mm;
2. The mean value of the density of all twelve specimen is $\rho_{u,mean}$ = 538.71 kg/m^3;
3. The characteristic density of all twelve specimen is ρ_k = 447.61 kg/m^3.

Table 2 Statistical results of the shear test in a scale of 1:2

shear test on specimen in a scale of 1:1	K_{ser} a ccording EN 26891 [N/mm]	$\rho_{u,mean}$ according EN 384 [kg/m^3]
quantity of specimen	3	3
mean value	29333.33	538.71
standard deviation	2801.03	55.21
coefficient of variation	0.10	0.10

2.2. Study on the load bearing capacity of teethed beams

2.2.1. Experimental procedure

To determine the flexural load bearing capacity of the teethed beams bending test according to EN 408 have been carried out. The used experimental arrangement is depicted in fig. 9.

A continuously increasing test load was applied on two points of the specimen with the help of a hydraulic pressure cylinder (maximum load 600 kN). The test load was measured with a electronic load cell. A trip wire displacement sensor was used to measure the deflection of the specimen.

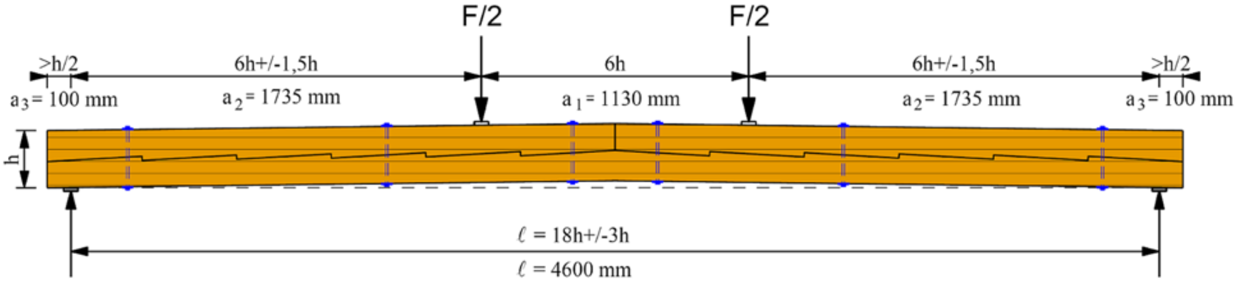

Fig. 9. Specimen for bending tests (scale 1:2) and experimental arrangement according EN 408

The end of the bending test was determined as a fraction in conjunction with a significant decrease of the test load.

2.2.2. Results of the shear tests

The bending tests in a scale of 1:2 according to EN 408 have provided the following results (see also fig. 10 and table 3):

1. The mean value of the maximum load is $F_{max,mean} = 57.76$ kN;

2. The mean value of the density of all twelve specimen is $\rho_{u,mean} = 520$ kg/m³;

3. The characteristic density of all twelve specimen is $\rho_k = 411.67$ kg/m³.

Table 3. Statistical results of the bending test in a scale of 1:2

	specimen 01	**specimen 02**	**specimen 03**
class according DIN 4074–1:2008	S13	S7	S10
strength class according EN 338	C30	C16	C24
maximum load F_{max} [kN]	64.79	57.07	51.43
deflection w [mm]	79.82	135.02	82.42
density $\rho_{u,mean}$ [kg/m³]	520	530	540
characteristic density ρ_k [kg/m³]	448	447	340
type of fracture	bending fracture	shear fracture	bending fracture

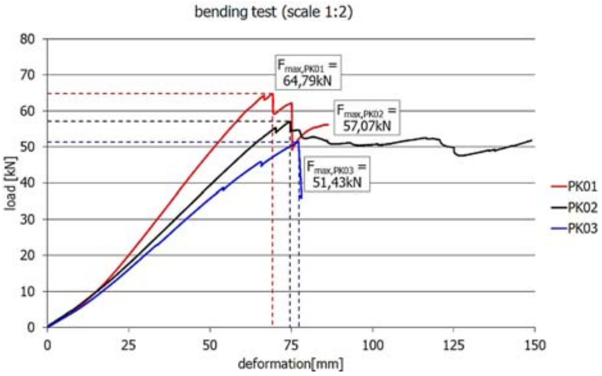

Fig. 10. Load-deformation curve, bending test in a scale of 1:2

Evaluation of the specimen's fracture – specimen 01:

The specimen No. 01 showed a large ratio of heartwood. Sapwood was only present on the narrow borders of the cross section. Upon reaching the maximum load a tensile fracture occurred on the bottom surface of the specimen. Here, the wood fibers ran out of the cross section. This led to a crack which continued over a length of ca. 2 meters along the fibers (see fig. 11). On the back side of the specimen a brittle fracture occurred in the sapwood which continued horizontal in the heartwood (see fig. 12).

Evaluation of the specimen's fracture – specimen 02:

The knot density on specimen 02 was relatively high (see fig. 13). This led to a complete respectively partial fracture of several tooth joints next to the sup-

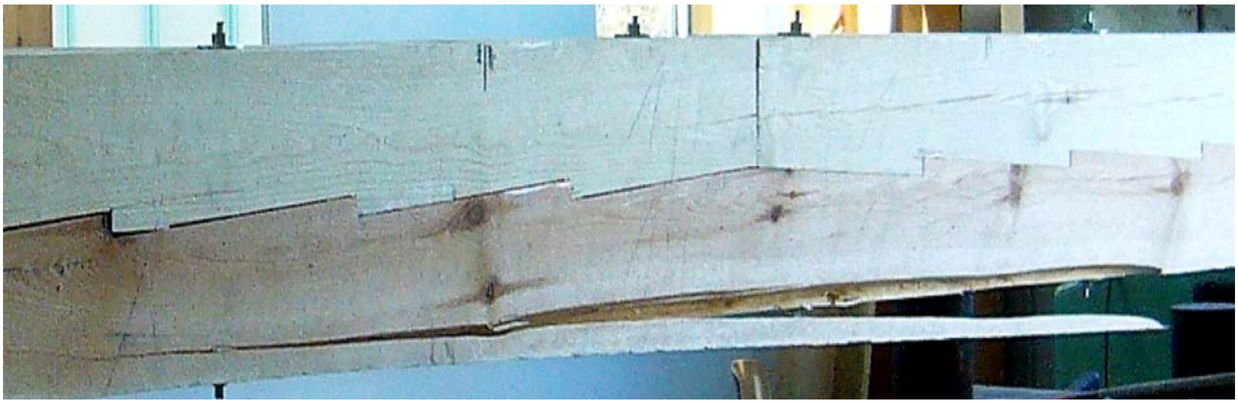

Fig. 11. Specimen 01 – tensile fracture on the bottom surface

Fig. 12. Specimen 01 – brittle fracture in the sapwood and horizontal cracks in the heartwood

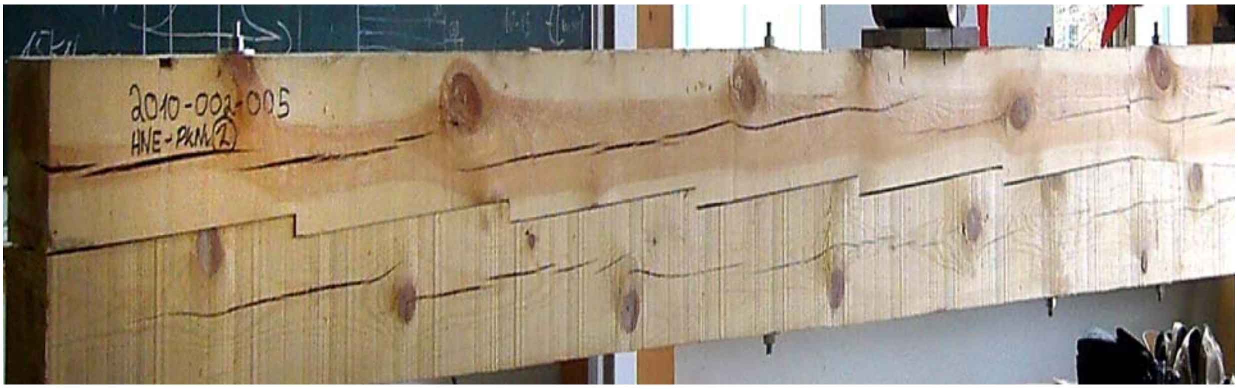

Fig. 13. Specimen 02 – relatively high knot density (before the bending test)

Fig. 14. Specimen 02 – partial fracture in the teethed joints due to knots

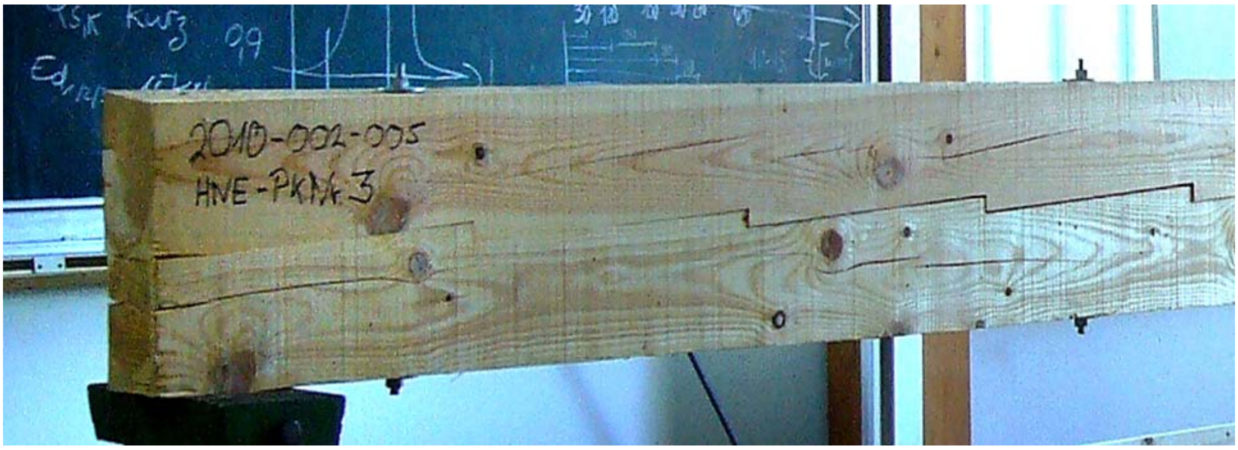

Fig. 15. Specimen 03 – relatively low knot density (before the bending test)

Fig. 16. Specimen 03 – fracture next to a knot on the bottom surface

ports. The direction of the load transmission in the teethed joints differed from the wood fiber's direction due to knots (see fig. 14). This difference caused a significant reduction of the wood strength. Since not all tooth joints failed simultaniously the specimen had not lost his load bearing capacity abruptly. This can also be seen in the load-deflection curve 8 see fig. 10).

The fracture of this specimen due to the relatively high knot density – especially in the tooth joints – shows the necessity of a targeted selection of high quality wood.

Evaluation of the specimen's fracture – specimen 03:

Despite the fact that the knot density of specimen 03 was lower than the knot denisty of specimen 02 (see fig. 15), the specimen 03 showes a clearly smaller increase in the load-deformation curve than the specimen 02 (see fig. 10). This means that the specimen took up less load at the same deflection, even though the wood quality was obviously higher.

The specimen 03 failed due to a tensile fracture next to a knot on his bottom surface (see fig. 16).

3. CALTULATIONS ON THE FLEXURAL LOAD BEARING CAPACITY OF THE TEETHED BEAMS

The load bearing capacity of a ductile composite beam – especially a teethed beam – can be calculated with three different methods:

1) γ-method according to EN 1995–1-1, appendix B

2) shear force analogy method according to EN 1995–1-1/NA, NCI NA.5.5.3

3) finite-elements method

The accuracy of the results of the γ-method is only given if the load is evenly distributed along the length of the beam.

In this case, the maximum load bearing capacity was calculated with the help of the γ-method. The calculations were carried out on basis of the characteristic material values for softwood of the strength classe C16, C24 and C30 according to EN 338.

According to the results of the static calculation the theoretical flexural tension stress equals the flexural strength at fracture of the estimated strength classes. Therefore, the results of the bending test have been proven by the results of the static calculation.

4. SUMMARY AND CONCLUSIONS

Composite beams with tooth joints were used for several centuries to bypass spanwidths of more than 6 meter. Despite, or perhaps because of the high requirements on their production these beams are an excellent example of the historical carpenters craftsmanship.

The empirical constructions rules for tooth joints were developed further in the course of the centuries. In the beginning of the 19th century these rules found their way into the literature. In the late 19th century, they were more and more displaced by easier to produce composite beams with dowel connections, although they had a higher composite action and load bearing capacity

The teethed beams can be calculated concerning their load bearing capacity according to the nowadays valid rules for dimensioning as long as the modulus of displacement of the tooth joints is determined. This gives the opportunity to use the teethed beams in accordance with the acknowledged technical standards. However, they will probably only be found in individual cases in the course of historical preservation work.

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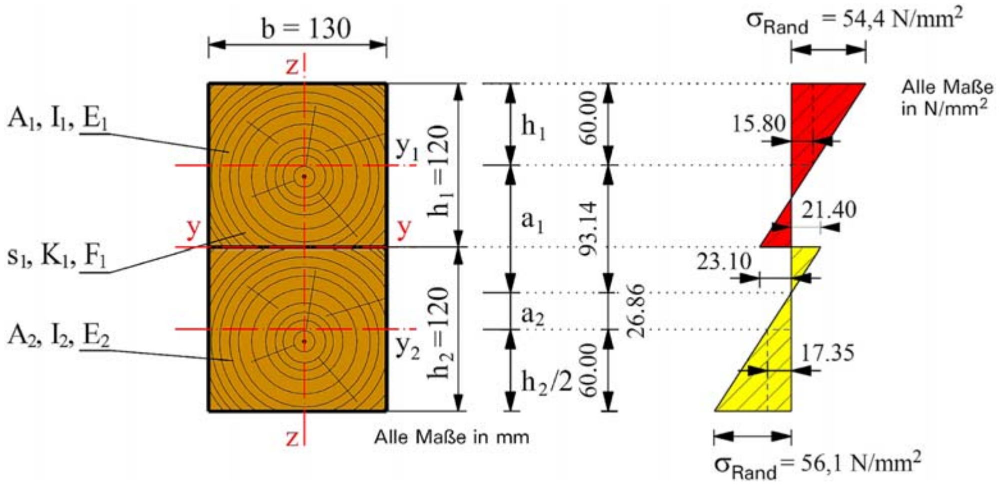

Fig. 17. Theoretical distribution of stresses, specimen 01 (class S13 according to DIN 4074–1:2008, strength class C30 according to EN 338)

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Abstract

A "teethed beam" is a composite beam consisting of multiple beams which are connected with sawtooth-like joints. These composite beams can already be found in illustrations of ancient roman bridges. Until the late 19th century these composite beams were used to realize large span widths with heavy loads – e.g. ceiling constructions in town halls and churches but also in bridges and roof constructions.

The teethed joint was supplanted due to the development of novel connection means like hard wood dowels, steel dowels and specifically designed dowels. Since the development of the glulam timber in the 20th century the teethed beams only played a role in maintenance. From a cultural heritage preservation's point of view these beams have to be preserved and maintained carefully.

The maintenance of a 270 year old church tower's roof construction is a good example for the preservation. In this case five teethed beams served as suspender beams for the ceiling construction which supported the roof construction. The teethed beams partially showed biotical damages on the supports so that they had to be replaced.

Unfortunately, there are no design rules for the teethed joint in the existing timber construction literature since the 1970s. Therefore, studies on the load bearing capacity and the load-deferral behavior of composite beams with teethed joints were carried out at the Univeristy of sustainable development Eberswalde. The results showed that the shifting modulus of a teethed joint is equivalent to the shifting modulus of a specifically designed dowel (type C1, Ø140 mm according to EN 912).

Streszczenie

Belka z połączeniami zębatymi to belka kompozytowa składająca się z kilku warstw połączonych złączami w kształcie zębów piły. Takie belki kompozytowe można zobaczyć na rycinach przedstawiających mosty z czasów starożytnego Rzymu. Do końca XIX wieku z belek tego typu korzystano przy realizacjach o dużej rozpiętości na szerokości i o dużym obciążeniu – np. konstrukcje stropów w ratuszach miejskich lub w kościołach, ale także przy budowie mostów i konstrukcji dachowych.

Połączenia zębate zostały wyparte z użycia w związku z rozwojem nowych sposobów łączenia elementów drewnianych, jak np. kołki z twardego drewna, kołki stalowe lub kołki specjalnego przeznaczenia. Od chwili pojawienia się drewna klejonego warstwowo (glulam) w XX wieku, belki z połączeniami zębatymi używane były tylko do konserwacji starych konstrukcji. Z punktu widzenia ochrony zabytków belki takie powinny być zachowane i odpowiednio konserwowane.

Dobrym przykładem zachowania belek z połączeniami zębatymi są działania konserwatorskie na liczącej 270 lat więźbie dachowej wieży kościelnej. W tym przypadku pięć belek o połączeniach zębatych służyło jako belki wieszakowe dla konstrukcji stropu, na której wspierała się konstrukcja więźby dachowej. Niektóre z belek z połączeniami zębatymi wykazywały w części uszkodzenia biologiczne w miejscach oparcia i musiały zostać wymienione.

Niestety współczesna literatura naukowa dotycząca budownictwa drewnianego od początku lat 70. XX wieku nie zawiera żadnych wytycznych odnośnie do projektowania belek z połączeniami zębatymi. Dlatego też na Uniwersytecie Zrównoważonego Rozwoju w Eberswalde przeprowadzono badania nad nośnością belek kompozytowych z połączeniami zębatymi oraz nad ich pracą w warunkach obciążenia fazowego. Otrzymane wyniki pokazują, że moduł podatności połączenia zębatego odpowiada modułowi podatności dla kołków specjalnego przeznaczenia (typ C1, Ø 140 mm zgodnie z normą EN 912).