Heritage Science

Historical scarf and splice carpentry joints: state of the art

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Abstract

This paper summarises the current state of knowledge related to scarf and splice carpentry joints in flexural elements, also providing some examples of tensile joints. Descriptions and characteristics of these types of joints found in historical buildings are presented. In addition, issues related to forming carpentry joints in historic and heritage structures are discussed. Next, analyses and studies of flexural elements as well as selected examples of tensile joints described in the literature are presented. It is worth noting that authors of vast majority of the publications cited draw attention to the need for further research in this area. They acknowledge that existing descriptions are incomplete and insufficient for bringing about precise understanding and correct description of the static behaviour of these joints. Knowledge about designing and assessing static behaviour of existing carpentry joints is an important issue and is necessary to properly design and strengthen existing joints in historical timber structures.

Keywords: Carpentry joints, Historical buildings, Scarf and splice joints, Stop-splayed scarf joints

Introduction

Wooden structures are one of the most common building types appearing over the centuries. Many of them have survived hundreds of years to the present day and constitute today not only a source of knowledge concerning technologies and engineering, but also about the culture and skills of craftsmen of by-gone years. In the main, many of these structures require today interventions to maintain and improve their technical condition.

One of the most important questions in the analysis of historical timber structures is that of carpentry joints. Thanks to carpentry joints, it was possible to join together building elements into a single whole. They provide for the transfer of forces between joined elements. Moreover, as a rule, the behaviour of the joints has a significant influence on analysis of the structure as a whole. The static behaviour of the joint influences internal forces in the structure, which is why undertaking a detailed analysis of the structure as a whole, requires analysis of the behaviour of the joints. The standard [1] recommends

taking into account joints displacement, but does not provide any guidelines on how to realise this recommendation. Resources available to date have been incomplete in this regard. Sufficiently detailed references on the topic of developing carpentry joints have not been worked out as craftsmen of past years relied on their experience and tradition. Determining the static behaviour of carpentry joints in historical structures allows for detailed analysis of the whole structure and provides a basis for making appropriate decisions relating to interventions that are acceptable from the perspective of conservation doctrines. The technical condition of the joint influences the stiffness of the whole structure and its load bearing capability. Over time and through the influence of loading and other external factors, carpentry joints in historical structures may become overworn or even completely destroyed, what can cause a serious threat to the building. Damage of the joints can become a danger for the whole structure due to significant weakening of element cross-sections where these join together.

Several hundred types of carpentry joints can be distinguished in historical structures [2], the form of which is linked to the development of construction craftsmanship and architecture in a specified geographical area

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or time-period. Categorisations of the different joints are based on their function (e.g. increasing in length or in cross-section dimensions, joining together elements [3] or between constituent parts of a single structural element and between elements in structural nodes [4]), form (e.g. pegged, notched, adhesive [5]), or their location in the structure.

In this paper, various forms of scarf and splice joints connecting elements in timber structures are presented as these were developed over the years. The development of joints geometry has been associated with their static behaviour. Although splice and scarf joints were historically designed mostly to carry axial loads, they sometimes have the ability to carry bending moments. For the purposes of this paper, a review of studies and analyses related to carpentry joints in flexural elements as well as selected examples of tensile elements described in the literature was prepared.
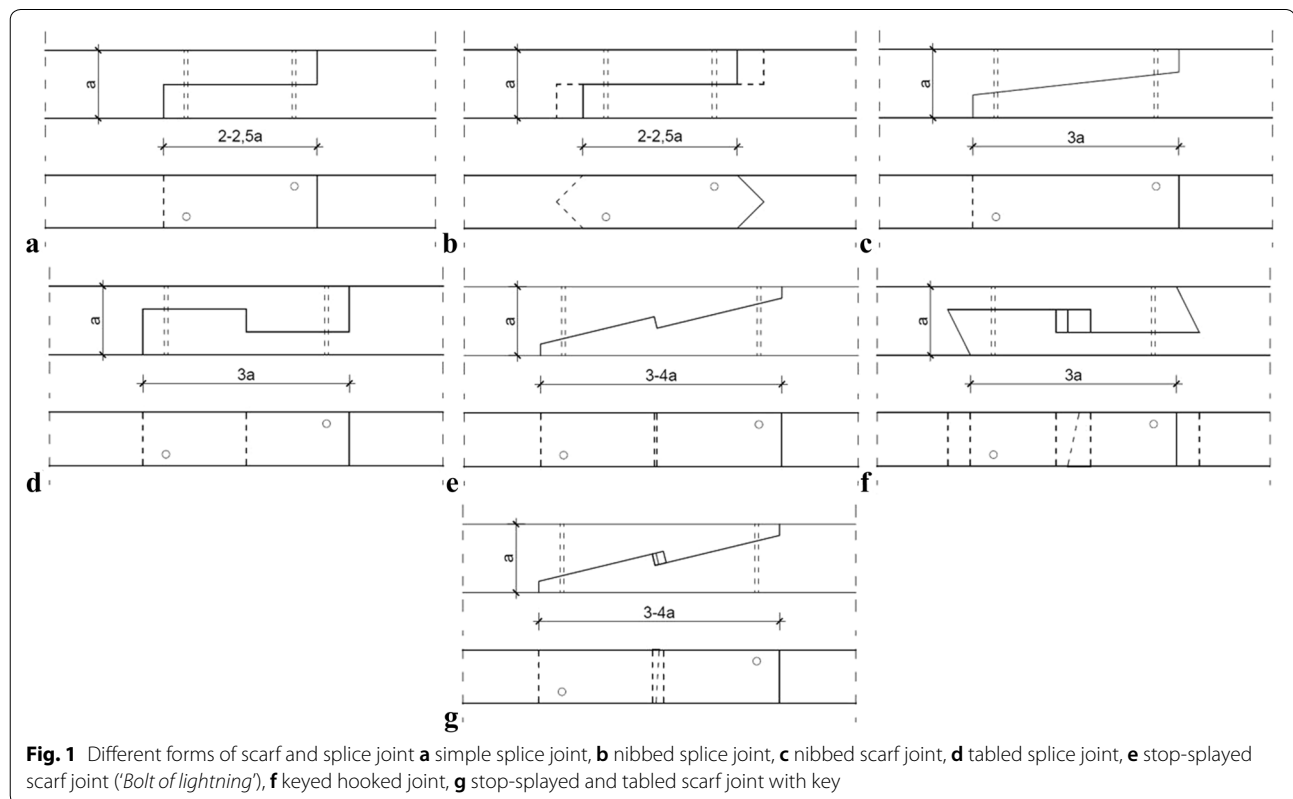
Characteristics of scarf and splice joints
Scarf and splice joints in historical structures
Scarf and splice joints enabled the joining of two elements lengthways. They were used when available materials could not provide the required piece length. Usually, wherever possible, they were applied in the least stressed cross-section because the joined elements could never achieve the same load bearing capability as that of a

solid cross-section [6]. In historical structures, aside from elongating ground and capping beams in building frames [7], scarf and splice joints were used to elongate roof elements. Up until the introduction of glue laminated timber technology, this was the common method for elongating wood elements [8]. Today, carpentry joints are used inter alia in the case of restoring historical joints or where the material need to be replaced in heritage elements. It is possible to distinguish several basic types of scarf and splice joints in historical structures, which were applied depending on their location in the structure and on the forces, which they needed to transfer (Fig. 1).

The simplest form for joining elements lengthways is the simple splice joint (Fig. 1a), which can be applied in both the vertical and horizontal plane as needed. The plane of contact is parallel to the two elements being joined as material is removed from each of the elements equivalent to half the cross-section height or width. Simple splice joints were sometimes applied with trimming or nibs (Fig. 1b). The nibbed scarf joint (Fig. 1c) is similar to the simple splice joint, but the plane of contact is diagonal in relation to the axis of the elements being joined. Aside from the forms detailed above, tabled splice joints (Fig. 1d), dovetail and stop-splayed scarf joints (Fig. 1e) are also found in historical structures. Sometimes such joints were additionally strengthened with pegs, which formed keys, e.g. keyed hook joint (Fig. 1f)

Fig. 1 Different forms of scarf and splice joint **a** simple splice joint, **b** nibbed splice joint, **c** nibbed scarf joint, **d** tabled splice joint, **e** stop-splayed scarf joint ('*Bolt of lightning*'), **f** keyed hooked joint, **g** stop-splayed and tabled scarf joint with key

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or the stop-splayed scarf joint with key (referred to in the literature also as the '*Bolt of lightning*', '*Trait-de-Jupiter*') (Fig. 1g). The pegs in these joints (Fig. 1f, g) were usually made from harder wood, ensured a tighter joint and made the joint easier to apply. From a mechanical point of view, this was a very beneficial type of joint as it allowed also for the transfer of bending stress.

Static behaviour of splice and scarf joints

It is obvious that elements joined together with these types of joint could not achieve the parameters of load bearing capacity or stiffness of solid elements of the same dimensions. Aside from the joint type, these parameters are influenced also by other factors, such as the actual dimensions of the elements being joined or wood strength parameters. The various forms of existing joints are a record of efforts undertaken in past times to form the strongest and the most durable joints in specified conditions.

The type of joint applied was dictated by the function that it had to serve, that is the type of loading which needed to be transferred. A simple nibbed scarf joint (Fig. 1c) could be applied in the case of connections with perpendicular loading and located next to supports. In such cases, the joint transferred shearing stresses. In the case of joining tensile elements it was essential to use a different type of joint. For tensile elements, stop-splayed scarf joints were applied (Fig. 1g). Such joints were pegged, which was supposed to help with load bearing capacity and ensuring stiffness of the joint.

According to analyses described in the literature [9], the indication is that in case of vertical load acting on element joined with a simple splice joint in the horizontal plane, the joint can transfer a bending moment equal to a quarter of the moment transferred by a solid beam. If the same joint was to be applied in the vertical plane, with the same loading, the value of bending moment that can be transferred is equal to half the value of the moment for a solid beam. This simple example illustrates just how important the joint type is for the static behaviour of longitudinal elements. In the case of nibbed scarf joints, which are more beneficial from the perspective of transferring shear stresses [10], the value of bending moment capacity constitutes only one-third of the load bearing capacity of an equivalent solid beam. It should be pointed out, that these examples are significant simplification of the problem. In fact, the connection between pieces with dowels or pegs affects decreasing the load capacity in some proportion. Although these examples can still show importance of the geometry of carpentry joints.

Stop-splayed scarf joints

A stop-splayed scarf joint (described inter alia in [11–14]) was a sophisticated form of joining elements lengthwise. However, it was commonly used in historical buildings. Elements joined along their whole length with so-called stop-splayed scarf joints are composite beams with a teethed joint (also known as built-up beams, which are described inter alia in [15–17]) (Figs. 2 and 3). They have been used since ancient times, e.g. in the construction of Roman bridges, and later in building elements forming wooden floors in town halls or churches, as well as in rafter framing right up to the end of the nineteenth century. A special development phase of this type of beam joint occurred during the Italian Renaissance period. With development of adhesive wood technologies, such as glue laminated timber, this type of joint is used today only in strengthening and repairing historical buildings. There are no rules provided in the available literature related to forming and dimensioning such elements.

The examples presented below showing forms of joining wooden elements lengthways were proposed by Renaissance masters, such as Leonardo da Vinci (Fig. 2a) [18] or Leon Battista Alberti (Fig. 2b) [19]. Figure 3f presents an example of carpentry joints formed using these templates in Italian heritage buildings, which have survived until today. Figure 2c presents an example of a joint in a roof beam of dimensions described in [11]. In Fig. 2d, the example of a composite beam from the fourteenth century palace in Verona is presented. Other examples from European architecture include the beams from the seventeenth century Church of St. Anthony in Ostrava [14], the church in Kargowa (Fig. 3a) or the Czocha castle in Lower Silesia, dating from the thirteenth century and rebuilt after a fire in the twentieth century (Fig. 3e).

The current state of knowledge related to research on carpentry joints

The importance of static analysis of carpentry joints

Designing and assessing the static behaviour of existing carpentry joints is an important issue. This is because there is a large number of preserved structures with such joints, which frequently require conservation interventions. Moreover, there is insufficient knowledge on the behaviour of such joints and a lack of standard recommendations for their design, which are needed for carrying out repairs or introducing replacements. In principle, three kinds of approaches to static analysis can be distinguished: experimental research, analytical calculations, numerical modelling. The first two approaches are the main source of data used for further analysis. They enable also verification of numerical models.
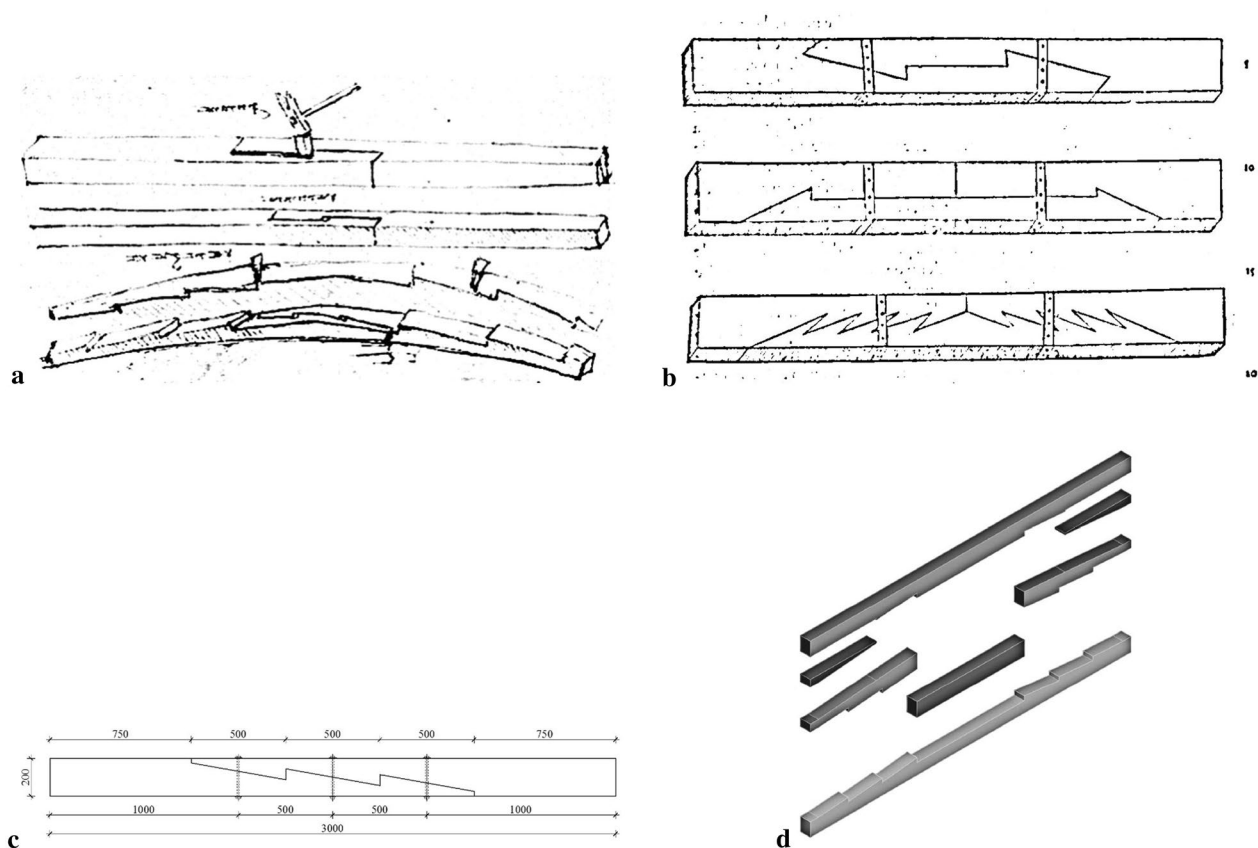
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Fig. 2 **a** Sketches presenting splice and scarf joints in wooden beams by Leonardo da Vinci [18], **b** sketches by Leon Battista Alberti [19], **c** drawing of a stop-splayed scarf joint with dimensions taken from an existing structure based on [11], **d** model of a composite beam from the fourteenth century palace in Verona [15]

The main aspects and tasks of the analysis of carpentry joints were above all the following [10]:

- determining stiffness and load bearing capability of the joint in relation to loading,
- mechanical properties of wood,
- checking compression stresses perpendicular to the grain between the surfaces of the joined elements (unknown pressure surface areas and uneven distribution of stress, compression at an angle to the grain, extension of the actual contact zone in line with recommended standards [1]),
- checking shear stresses distribution in the joint.

As carpentry joints constitute an important aspect in the analysis of timber structures, research on their static behaviour, repair and strengthening methods is ongoing.

Research on carpentry joints in historical structures has been, and continues to be, undertaken by many researchers in many different regions of Europe (mainly in Italy and in Portugal, but also in the United Kingdom, Germany and more recently in the Czech Republic) and also globally (e.g. in the USA and Japan). The state of the art/ review of up-to-date research and analysis on historical carpentry joints is presented in Tables 1 and 2. The main focus of analyses were notched joints (inter alia in [20–22]) and tenon joints (inter alia in [23–25]). Analyses have also focused on tightening tenon joints with pegs and pins (e.g. in [26]). Research is underway on the behaviour of joints under static loading and also when loading is dynamic (inter alia in [27–30]) and on determining failure modes (e.g. in [7]). Research is concerned with joints on their own, as well as with whole structures, e.g. roof trusses (inter alia in [31–34]). Methods of strengthening traditional joints are also proposed (e.g. in [11, 35–37]). These, however, relate above all to notched joints and also to mortise and tenon joints. There is decidedly less research under way on flexural joints. Moreover, all researchers who have undertaken research on flexural joints (in the Czech Republic [38–50], United Kingdom [51] or Germany [16, 17]) underscore the fact that research is still needed to enable an adequate

Fig. 3 Examples of joints in existing building structures: **a** Church in Kargowa—stop-splayed scarf joint, **b** Church in Skepe—plain splice joint, **c** Church in Skepe—plain key joint, **d** Palace in Żagan—splice joint, **e** Czocha Castle—stop-splayed scarf joint, **f** historical building in Italy (photo: author)

Table 1 Review of up-to-date research and analysis on historical carpentry joints

Type of carpentry joints	Experimental research	Numerical analysis	Analytical description
Notched joints	✓	✓	✓
Tenon joints	✓	✓	✓
Splice and scarf jonts	✓[a]	✓[a]	✓[a]

[a] According to the authors: incomplete and insufficient research, need for further analysis

description of the static behaviour of joints and to propose the most beneficial repair or strengthening methods for these joints.

Flexural joints

Kunecký et al. carried out testing of flexural lapped scarf joints with inclined faces (described in [38–40, 46–49]). Experimental testing and numerical analysis were aimed at determining the effective behaviour of the joint in

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Table 2 Review of research and analysis of different types of historical carpentry joints

Type of carpentry joints/element with joints	Authors' country	Experimental research	Numerical analysis	Analytical description
Flexural joints/elements				
Lapped scarf joint with inclined faces	Kunecký et al., Czech Republic	✓	✓	
Scarf joints with pins or keys	Fajman et al., Czech Republic	✓		✓
Splice and scarf joints with pegs (under-squinted butt in halved scarf, side-halved and bridled, stop-splayed and tabled scarf with key, face-halved and bridled scarf)	Hirst et al., United Kingdom	✓		
Composite beam with stop-splayed scarf joints	Mirabella-Roberti et al., Italy		✓	
Composite beam with stop-splayed scarf joints	Rug et al., Germany	✓		✓
Halved and tabled scarf joint and stop-splayed scarf joint with key	Sangree et al., USA	✓	✓	
Tensile joints/elements				
Halved and tabled tenoned scarf joints	Aira et al., Spain	✓	✓	✓
Stop-splayed scarf joints with keys	Ceraldi et al., Italy	✓		
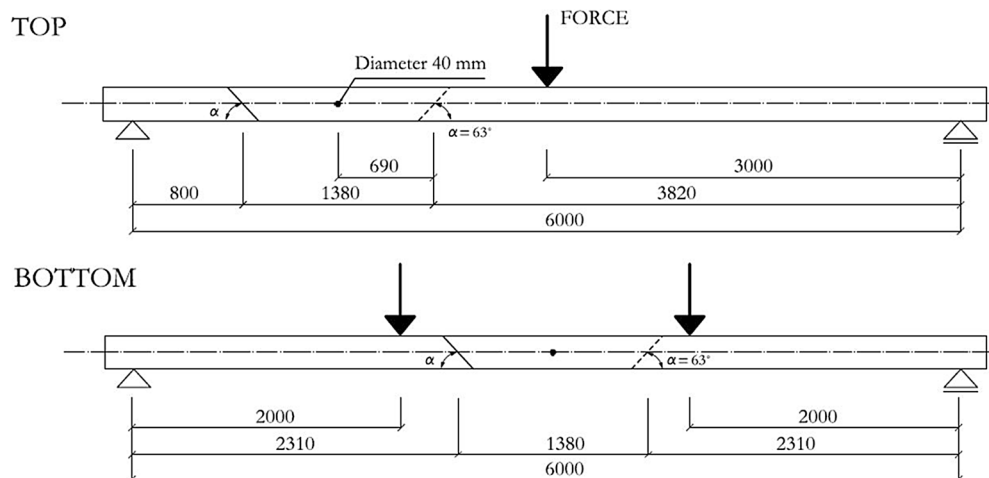
Fig. 4 Beam models with lapped scarf joints with inclined faces subjected to flexural three point testing (TOP) and four point testing (BOTTOM) according to [47]

relation to mechanical parameters. The influence of the number of pegs, geometry and location of the joint along the length of the beam in relation to its load bearing capacity and stiffness were all analysed. The testing was carried out on beam models 6 m in length with a diagonal cross-section of 200 by 240 mm, and included three and four-point flexural testing. The model used by these researchers is presented below (Fig. 4).

It was determined how the various parameters influence the static behaviour of the joined element and which variation constitutes the most beneficial solution [39]. The tests showed that in this case, the most effective solution was that of a joint consisting of three pegs with equal notches of half the width of each of the joined elements. Locating the joint closer to the support increases

the load bearing capacity of the beam (limiting forces around the pegs). Reducing the length of the joint results in a decrease in load bearing capacity and stiffness of the beam (increased forces on the pegs). In practice, according to the researchers, for 6 m beams, the 1.38 m long lapped scarf joint with inclined faces and three wooden pegs, located at one-fifth of the length of the beam from the support was the most beneficial solution. In terms of strength (load bearing capacity), stiffness and workmanship. This relates to the situation where there is a need for the end of the beam to be replaced. The authors underscore that locating such joints during renovation work must take into account, above all, the need to conserve as much as possible of the original material and to limit to the maximum extent possible the damage, which brought
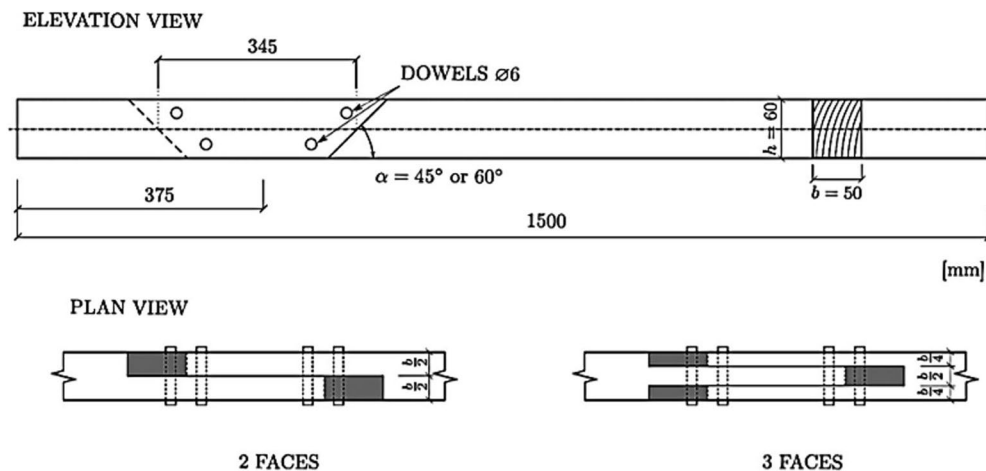
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Fig. 5 Models of single (left side) and double (right side) diagonal lapped joints—so-called bridled according to [38]

about the intervention in the first place. Moreover, it was determined that using the joint analysed could provide 65–75% of the load bearing capacity of the original beam, whereas its stiffness is largely unchanged.

In [47, 49] reports on research on a joint with a single pin are presented. The research addressed the influence of individual geometric parameters. Experimental testing was carried out and the results were subsequently verified by numerical analysis. The models were subjected to four point flexural testing to obtain a bending without shearing and three-point flexural testing to obtain bending with shearing. The test involved using a steel pin. Typical failure modes for the tested joints were also presented: degradation of the material around the peg and cracking of the wood due to shear stress and also failure of the diagonal surface caused by force applied perpendicular to the grain. The test results confirm the high stiffness level as compared to the reference solid beam, which depends on the position of the peg as this influences the distribution of forces in the joint. The angle of the inclined surface in the joint has the largest influence on stiffness. The vertical location of the pin and its dimensions have a smaller influence on the result. The load bearing capacity of the joint is maintained at a level of over 50% as compared to the solid beam. The results of the numerical analysis indicate that the configuration of the joint (geometry and number of connectors) has only a small influence on the load bearing capacity of the element [46, 47].

Tests of the same joint under complex loading conditions have been described in [40]. These were supposed to reflect the actual loading in timber roof framing elements: compression with bending in the case of rafters and tension with bending in the case of frame elements.

The experimental testing was carried out in smaller scale models. This was followed by a wider numerical analysis based on applying the finite elements method. The strength and stiffness of the joint were assessed from the perspective of conservation interventions in historical structures, taking into account their aesthetics (for single and double lapped joints, so-called bridled) (Fig. 5).

Based on their analyses [38, 40], the authors conclude that when repairing rafters (subjected to bending and compression), it is recommended to apply joints with planes tilted 60°, whereas in the case of beams subjected to bending and tension an angle of 45° for the joint is more beneficial (both from the perspective of load bearing capacity and stiffness). Moreover, the research indicated that failure of joints in tensile beams is related to the load bearing capacity of the peg connectors used. The authors describe the failure mode, on the basis of which it is possible to estimate load bearing capacity and stiffness of the joint. It is true that bridled joints are more complicated and time-consuming to apply, but they are a more beneficial solution from the point of view of mechanics when compared to simple splice joints. As a result, this is a solution that is recommended by the authors in interventions involving beams requiring larger load bearing capacity. It was also estimated that with this type of joint, the load bearing capacity of such beams was approx. 60% of the original (solid) beam, and it was also concluded that the stiffness of a composite beam did not change significantly.

Aside from experimental research and numerical analysis, the authors carried out also tests using digital image correlation, in accordance with inter alia [34, 47, 48]. The benefits of using different testing methods were

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underlined as being complementary to one another and so leading to better (more accurate) results.

In [48], the authors used this method to investigate the length of the contact on the diagonal face of the joint. This parameter influences the distribution of stresses and constitutes an important part of the analysis of the whole structure. The authors point out that there are no discussions of this question in the literature, except for a few descriptions of loosened joints with a limited zone of contact between the connecting surfaces. Usually it is assumed that the contact zone involves the whole length and remains unchanged over time (ideal case), whereas the reality can be quite different. The research method used by the authors is effective and allows essential information relating to the zone of contact to be generated quickly. The values of the contact length obtained differed in relation to load bearing models (four and three point bending).

The question of failure modes in composite beams has been investigated in inter alia [39, 48]. In a numerical analysis based on the finite elements method, carried out by the authors, the failure mode is related to the distribution of forces around the pins and wood failure resulting from tensile stresses perpendicular to the direction of the grain in the vicinity of the pin openings. Failure of the whole joint takes place when the pin connector fails, as it is subjected to the largest loading. The value of the failure loading can be estimated by applying standards or parameters from the literature based on Johansen's theory, which assumes a plastic failure. Some researchers posit that the brittle splitting failure method should also be considered (see for example [39, 48]).

In Milch et al. [34] describe the behaviour of dowelled joints built in technical scale models made from pine wood (*Picea abies* L. Karst.) and oak wood (*Quercus robur* L.), taking into account different dowel sizes (12, 16, 20 and 24 mm in diameter). The joints were subjected to tensile stress in accordance with the EN 339 and EN 26,891 standards. The authors determined the slippage and load bearing modules based on displacements and the force distribution investigated for dowels of differing diameter by means of the digital image correlation method, and also on the basis of theoretical considerations, which included inter alia Johansen's theory.

Fajman et al. (inter alia in [41−45, 50]) relate analytical models and the results of experimental research concerning nibbed splice and scarf joints in vertical planes with pins or keys (Fig. 6). These can used for example to repair flexural elements, e.g. structural ceiling beams [41].

The research analysed joints in different configurations, i.e. with strengthening with pegs and pins and also different locations along the length of the beam of the joints tested (at the end of the beam, in the middle of the beam
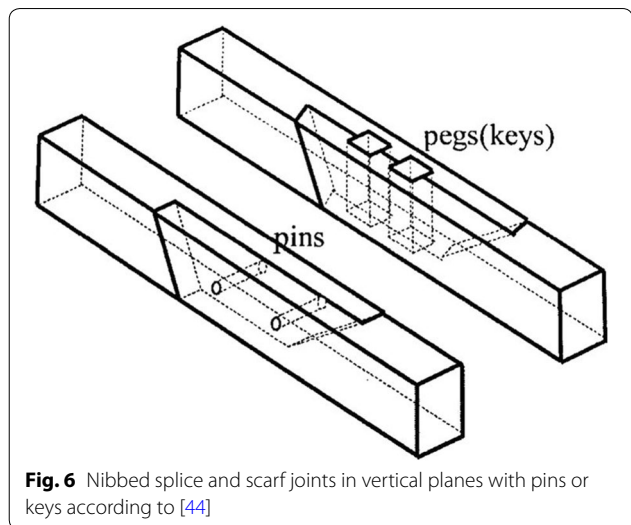

Fig. 6 Nibbed splice and scarf joints in vertical planes with pins or keys according to [44]

span). The elements were subjected to three or four point flexural testing depending on location. The authors of the research state that in most cases the deciding factor for these elements is the serviceability limit state [44]. It was hard to determine precisely the forces appearing in a nibbed splice and scarf joint with keys (Fig. 7a) and pins (Fig. 7b). It is also not known exactly, which angle of inclination and what number of pegs is the most beneficial. According to authors, these kinds of joints with four pegs are recommended for example in Germany, which is not justified from the point of view of the statics (mechanics) of the joint. The authors state that there is no significant difference in static behaviour of joints with two and four pegs [41, 44].

Joints with pegs are used universally in the repair of historical timber structures [43, 50]. It is possible to use wooden keys (pins) or combinations of these. Currently, in the literature, there is practically no information on the static behaviour of such joints, even though this is needed by contemporary engineers. The analyses of these authors lead to some practical conclusions. The values obtained for displacements are the same when calculated using analytical methods and when obtained through experimental testing for splice and scarf joints in elements loaded to the bending moment and shearing force. The values for stiffness of joints with pins and clasps are comparable [41, 44]. In the case where the deciding factor is the serviceability limit state, the load bearing capacity of the joint is not fully exploited. In such a case, the effectiveness of both solutions is comparable.

The results of research carried out at the University of Bath in the UK by the team of Walker, Harris, Hirst et al. [51] concern static behaviour of scarf joints, which are most common in historical structures across England.
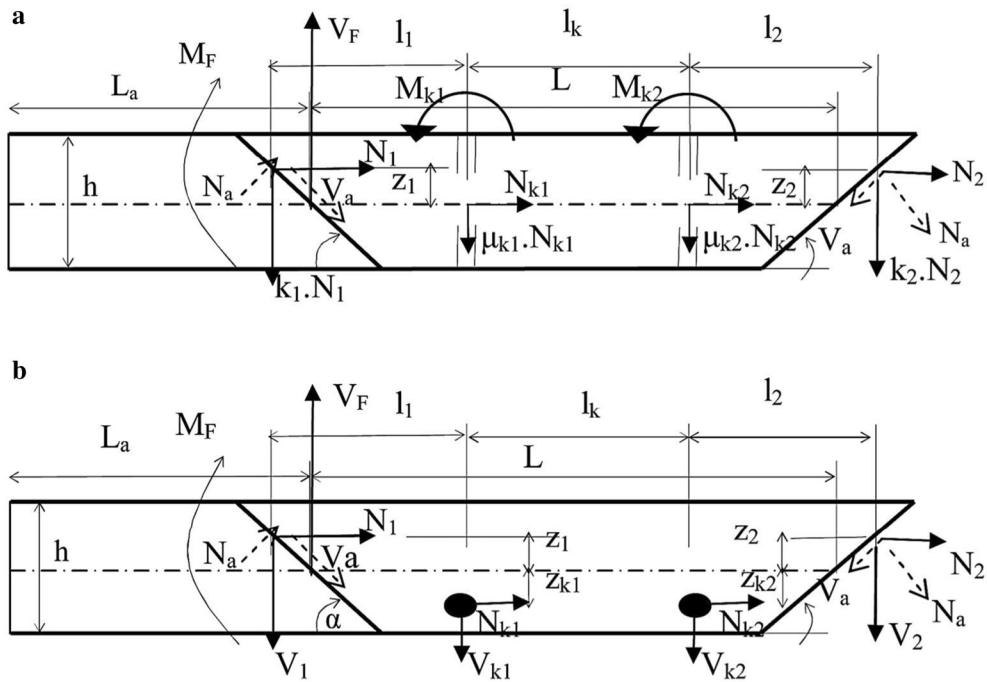
Fig. 7 Schematics showing the distribution of forces in joints **a** with two keys, **b** with two pins [44]
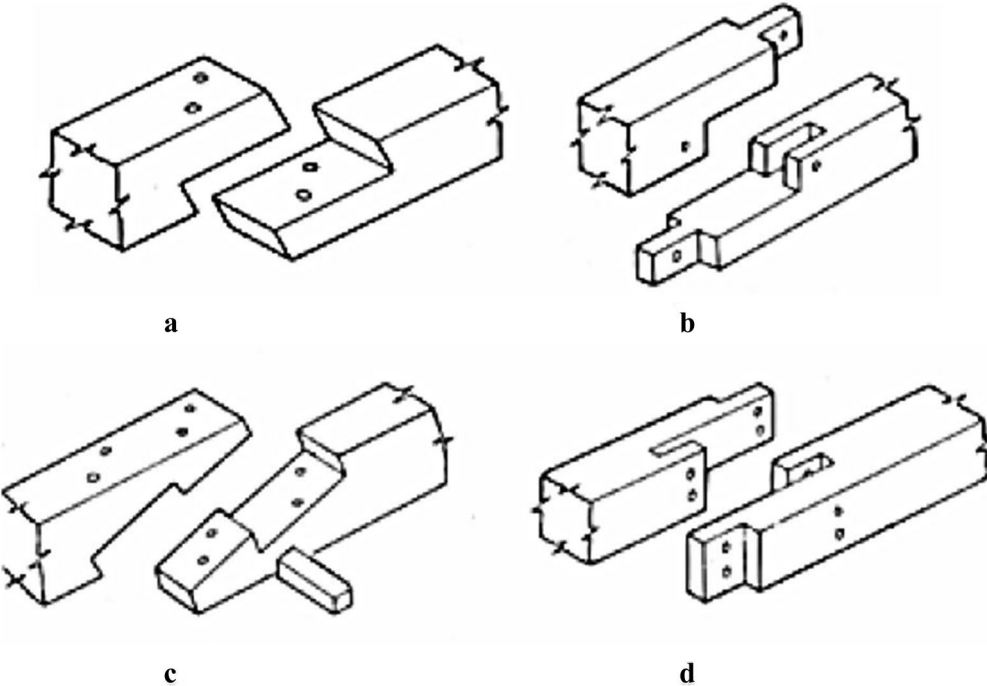

Fig. 8 Splice and scarf joints analysed in research in [51]: **a** under-squinted butt in halved scarf with two pegs, **b** side-halved and bridled with two pegs, **c** stop-splayed and tabled scarf with key and four pegs, **d** face-halved and bridled scarf with four pegs
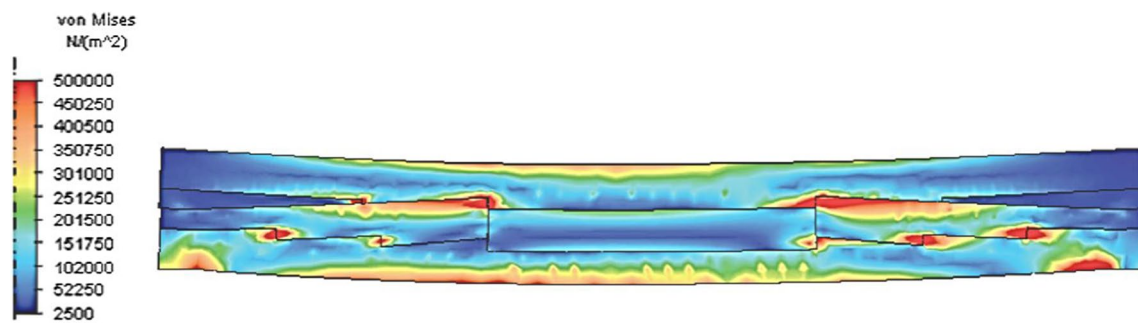
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Fig. 9 Stress map showing places of concentration based on numerical analysis in accordance with [15]

The joints research includes: under-squinted butt in halved scarf with two pegs, side-halved and bridled with two pegs, stop-splayed and tabled scarf with key and four pegs, and face-halved and bridled scarf with four pegs. The authors underline that making the openings for the pegs involved displacement in both the elements being joined in order to allow tightening of the joint after insertion of the peg (see for example [9]). The joints analysed are presented below (Fig. 8).
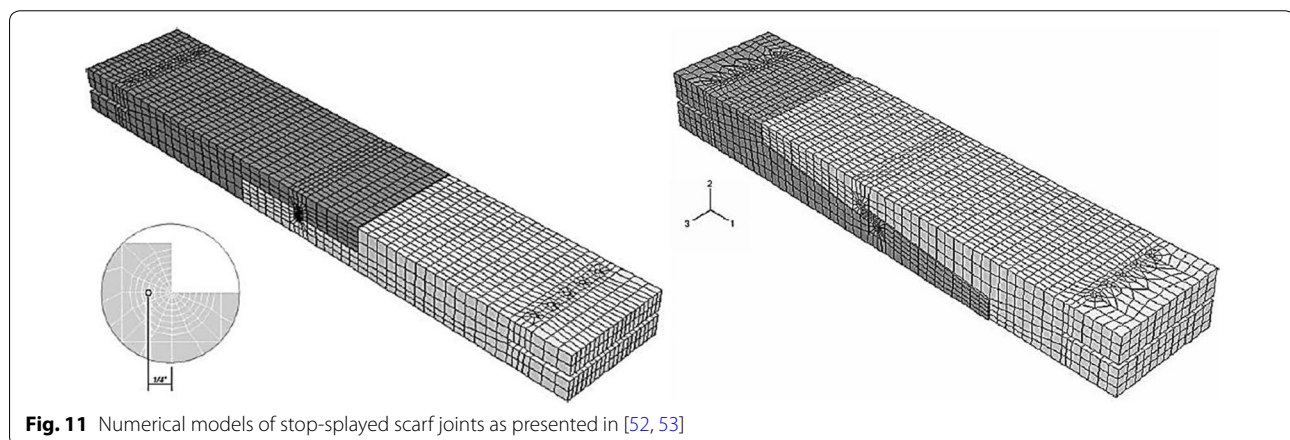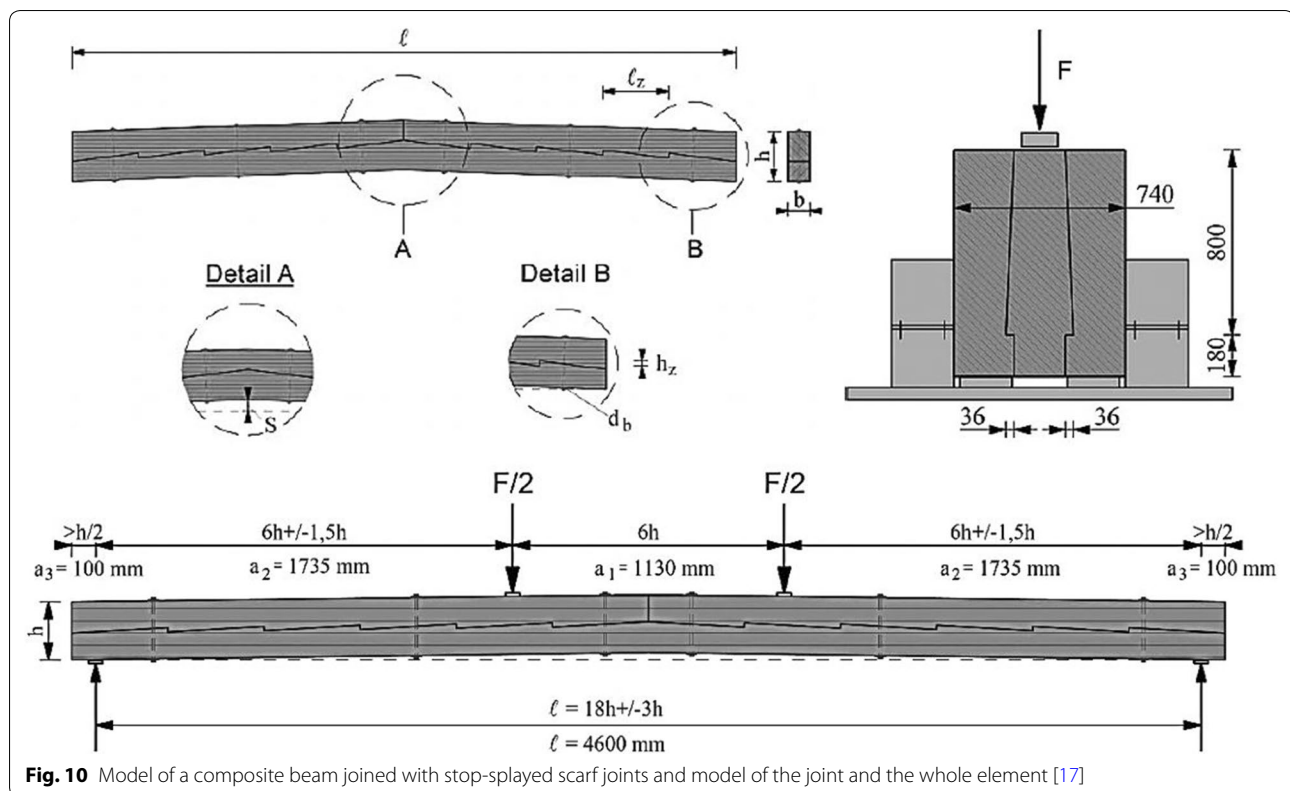
Experimental research [51] was carried out on beam models 2.5 m long joined using the joints listed above and 1.5 m solid beams for comparing results. The elements were subjected to four-point vertical bending and lateral bending tests to attain clean bending. Static equilibrium pathways (load–deflection plots) were determined and these provided a basis for comparing results for join variations and parameters in relation to solid beams. The performance factor or the loading and stiffness of the composite beam in relation to the solid beam was determined. The largest stiffness was observed in the case of the side-halved and bridled joint and the stop-splayed scarf joint in response to vertical bending. The largest load bearing capacity was observed for the key in the stop-splayed scarf joint (28% as compared to the solid beam) and in the face-halved and bridled scarf with four pegs (24% as compared to the solid beam) when bending in the vertical plane. The authors report that all the beams initially displayed near linear behaviour under small loading, even though wood has been described as a material that is non-linear inelastic. All the joints were characterised as displaying plasticity when loaded and prior to failure. The failure modes are also described. As the pegs in the tested joints were made out of high quality material, failure was caused by failure of the beam wood and not that of the peg. The important factors to take into account in designing these types of joints were highlighted in the conclusions: joint length, optimisation of peg use and orientation of the joint in relation to the direction of loading. The researchers underline, however,

that the results obtained are not entirely reliable, if only because of obtaining in some cases an abnormally high performance factor value. In order to obtain reliable results, the need is to carry out further and more detailed testing on the joints discussed above.

In Mirabella-Roberti and Bondanelli [15] presented individual analyses of flexural elements, which are so-called composite beams, joined lengthways with stop-splayed scarf joints. Applying a numerical analysis, the authors discovered the places where the highest stress concentrations would likely occur, especially near to the joint edges (Fig. 9).

Rug et al. [16, 17] present rules for forming and dimensioning the beams described above based on the literature up to the 1970s. Today it is hard to discern rules concerning the construction or reconstruction of such elements. For this reason, research was undertaken at the University of Eberswalde in Germany to determine the load bearing capacity of such elements and their static behaviour described in terms of displacement due to the influence of loading applied to them. The experimental testing was carried out on physical models constructed in 1:1 technical scale (the dimensions were determined to be those of an existing wood frame structure of the tower of one of Germany's churches) and also on models scaled at 1:2. Flexural tests were carried out (in accordance with EN 408), and an average load bearing capacity of 57 kN was obtained. A loading-displacement curve was determined, as well as the modulus of joint displacement in the physical model (in accordance with EN 26891). The experimental models described are presented below (Fig. 10).

The studies present also ways of calculating the parameters of composite beams subjected to testing: the method for calculating parameter γ (parameter introduced in EN procedure when calculating the equivalent bending stiffness for complex section) is presented in attachment B of the EN 1995 standard (assuming loading is evenly spread along the whole

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Fig. 10 Model of a composite beam joined with stop-splayed scarf joints and model of the joint and the whole element [17]

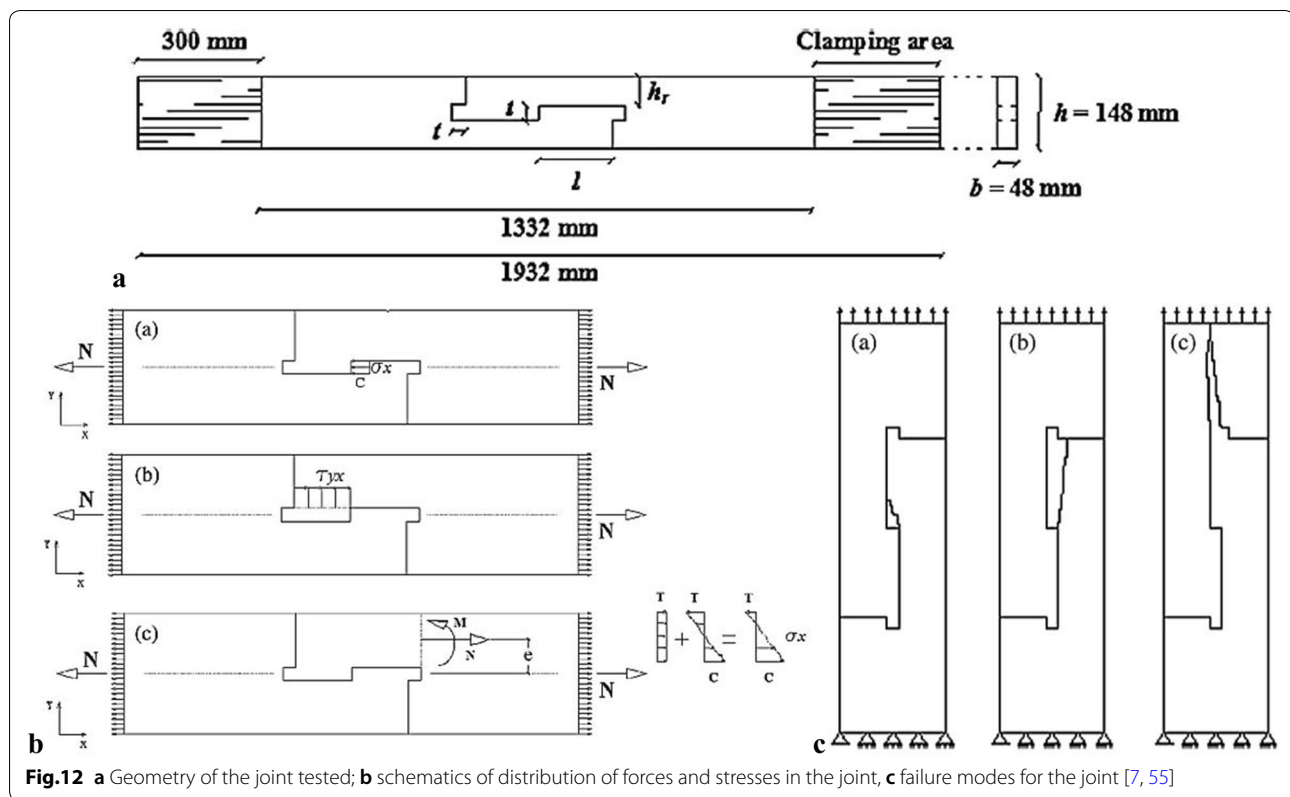**Fig. 11** Numerical models of stop-splayed scarf joints as presented in [52, 53]

length of the beam), the shear force analogy method which is included as an annexe to the national (German) EN 1995 standard and the finite elements method. These calculations are possible if the value of the modulus of joint displacement is known. It is worth noting that also in this case, the authors underscore the need for further research on this topic.

Research on joining composite elements with scarf joints has also been undertaken by inter alia Sangree and Schafer in Baltimore, USA [52, 53] for the halved

and tabled scarf joint and stop-splayed scarf joint with key. These joints were used in traditional timber structures, e.g. in the Morgan Bridge, in which is presented by the researchers. Their research involved using actual scale model joints. The results of experimental testing was verified by numerical analysis (Fig. 11).

The researchers underscore that this type of joint should be analysed as an element that functions under complex loading conditions: tensile bending. In the case of the halved and tabled scarf joint [52], the authors

Fig.12 a Geometry of the joint tested; **b** schematics of distribution of forces and stresses in the joint, **c** failure modes for the joint [7, 55]

describe two failure modes for the joint: through shear failure parallel to the grain or tension failure perpendicular to the grain. The research indicates that the stiffness of the joint is low as compared to the stiffness of a solid element. In the case of stop-splayed scarf joints with keys [53], the researchers concluded that the orientation of the key has the greatest influence on the static behaviour of the joint as it generates compression perpendicular to the grain. Aside from this, they direct attention to the presence of draw bolts which are essential for maintaining the connection. In such cases, it is possible to obtain shear failure parallel to the grain, which allows for a higher level of stress. The authors note that the joints can be modelled based on the contact between the elements, using the stiffness value obtained from experimental data. Stiffness was addressed in terms of linear-elasticity. The material model adopted was that of a cross-wise isotropic material. In addition, modelling lateral gaps in the stop-splayed scarf joint without key allowed for a quantitative determination of the reduction of the stiffness of the joint.

Tensile joints
Some studies focused on joints with keys (including stop-splayed scarf joints), which were subjected to tensile loading (inter alia [7, 37, 54, 55]). Failure modes are presented and also proposals on how to strengthen the joints investigated. Descriptions of the research carried out on tensile joints are presented below.

Analysis of halved and tabled tenoned scarf joints are presented in [7, 55] and in Fig. 12a.

The objective of the research was to identify the failure modes for joints subjected to tensile forces. Three different failure modes were observed (Fig. 12c): compression parallel to the grain in the notch area, shear parallel to the grain in the heel surface, cracking starting in the reduced cross-section. The loading which initiated cracking was determined. The influence of the length of the toothed zones on the value of the failure force was also analysed. The maximum tensile force transferred by the joint was limited by the appearance of cracking and was significantly lower than the maximum value for a solid beam.

In [54, 55] a numerical and analytical model of analysed joint is presented. It was proposed to include steel clasps or keys in order to tighten the joint and
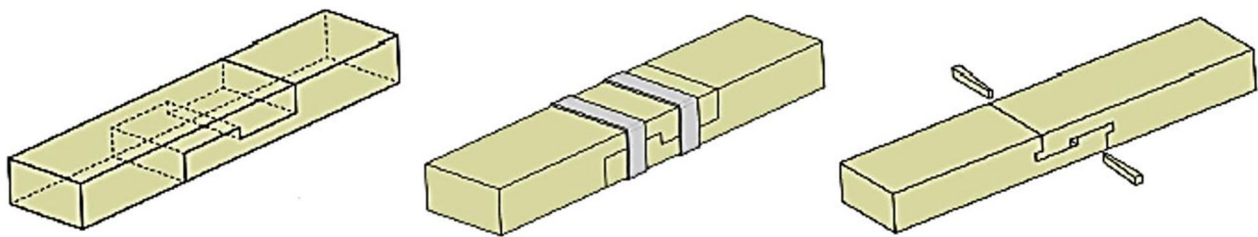
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Fig. 13 Key joints with steel clasps and keys in accordance with [54]

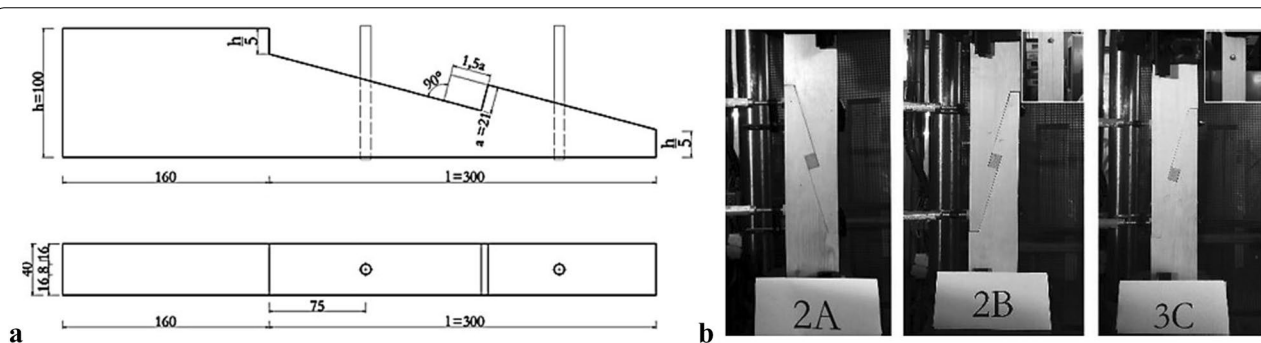**Fig. 14 a** Geometry of a stop-splayed scarf joint, **b** view of the experimental research station used for carrying out tensile tests [37]

ensure that the connecting faces of the joined elements abut (Fig. 13). The distribution of stresses in the joint was analysed, along with zones of stress concentration and the results of the two methods were compared. The results were found to be consistent from the two methods (apart from the locations in which the stresses were concentrated). The authors considered also the influence on the final result of the size of the grid size adopted for the joint in the numerical modelling.

An analysis of the behaviour of stop-splayed scarf joints with keys subjected to tensile forces is presented in [37] and in Fig. 14. The authors analysed various ways of strengthening the joint: with the help of timber pegs and steel pins.

In this research, an increase in stiffness of 41% was noted for the joint with clasps and of 52% for joints with steel pins. The increase in the yielding force values was also analysed. Load–deflection plots were prepared and the failure modes were identified. The authors draw attention to differences in the static behaviour of the joint, which depend on the material used for the connecting pins (wood, metal).

Adhesive joints

In the case of repair or partial replacement of a damaged element in historical timber structures where the aspiration is to preserve the original shape and static scheme, Rapp et al. propose using adhesive scarf joints [56–58]. The studies present an analytical model of adhesive scarf joints (Fig. 15) assuming plane linear elasticity and an orthotropic material model.

The joint can function in complex loading conditions: influence of axial force, bending moment and shearing force. The model of the joint is described in terms of displacements (a set of four partial second order differential equations). The authors present their solution to the question using plasticity theory. It turns out that adhesive joints of low joint displacement between two elements comprised of the same material and thickness, transfer forces in the same or similar way as in a solid element (considered as a joint in which the adhesive is non-deformable). It was also demonstrated that in adhesive joints, there is no concentration of stresses in the adhesive and the state of stresses and displacements in the element with joints is similar to that of the solid element without joints. A numerical model which was developed
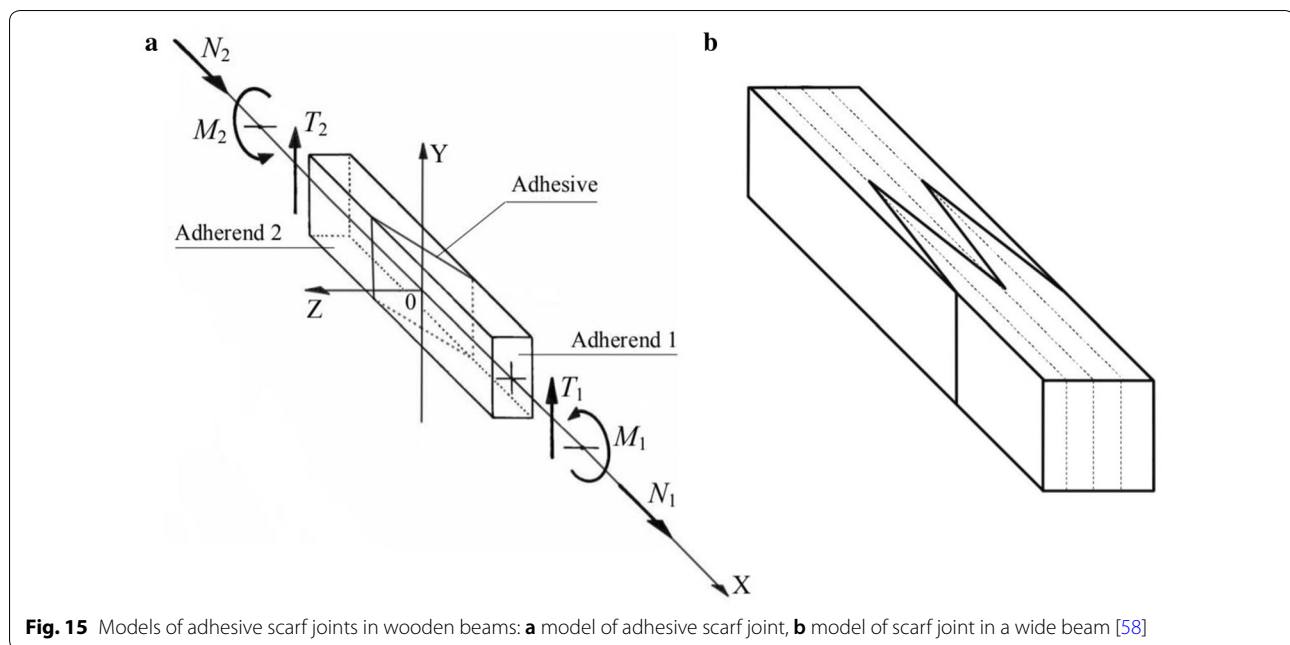
Fig. 15 Models of adhesive scarf joints in wooden beams: **a** model of adhesive scarf joint, **b** model of scarf joint in a wide beam [58]

in addition, confirmed the accuracy of the analytical model.

Summary and findings from the state of knowledge analysis

Tables 3 and 4 list the literature analysed, and present their findings and analysis concerning carpentry joints in flexural elements and some especially interesting examples of tensile joints.

As it is evident from the listing above, the literature includes some analyses of carpentry joints in flexural elements, but there are not many of them. In practice, all the researchers underscore the need for more experimental research in this area, acknowledging that existing information is insufficient for bringing about more precise understanding and correct description of the static behaviour of these joints.

Large differences can be observed in the values obtained for load bearing capacity or stiffness of the flexural elements tested. These result, above all, from differences in geometry of the joint (inter alia its length, dimensions, angles of incline in the case of sloping surfaces etc.), as well as its location in the element, the additional strengthening applied to the element, such as pegs, keys, metal pins or other types of strengthening. This finding confirms the importance of adopting a correct geometry when forming new carpentry joints, repairing old ones or strengthening existing joints.

Some of the research programmes presented are concerned with scarf joints subjected to tensile loading.

The findings of these analyses could be of interest also for understanding joints in flexural elements.

One of the most interesting examples of scarf joint in wooden elements appears to be the stop-splayed scarf joint known in ancient times and universally used during the Italian Renaissance (by such masters as Leonardo da Vinci or Leon Battista Alberti). Examples demonstrate that this type of joint can transfer both tensile and flexural loading when appropriate strengthening is applied (whether in the form of pins, keys or steel clasps). This type of joint can be used in conservation or renovation work in heritage structures. An appreciation for the static behaviour of the joints can enable an optimal restoration that is in line with conservation doctrine.

In terms of final conclusions, it can be stated that there is an evident need for further research aimed at securing a more precise depiction of the static behaviour of joints in flexural elements, especially when it comes to stop-splayed scarf joints.

As a consequence in response to the need for additional research in the topic, experimental research on the static behaviour of different types of scarf joints in flexural elements was carried out at Wroclaw University Science and Technology (as part of a research project financed by the National Science Centre). The goal was to determine the load bearing capacity and stiffness of joints subjected to bending, as well as to determine the influence of the type of joint and the method of its strengthening on these parameters. For the purposes of experimental testing, beam models in

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Table 3 Characteristics of research models

Publication year, authors	Research model	Load bearing capacity of the joint (if given)
Flexural joints		
2014–2018, Kunecký, Sebera, Hasníková, Arciszewska-Kędzior, Tippner, Kloiber et al., inter alia [5]	Lapped scarf joint with inclined faces	65–75% load bearing capacity of a solid beam
2014–2018, Kunecký, Sebera, Hasníková, Arciszewska-Kędzior, Tippner, Kloiber et al.; inter alia [46, 47, 49]	Lapped scarf joint with inclined faces	50% load bearing capacity of a solid beam
2014–2018, Kunecký, Sebera, Hasníková, Arciszewska-Kędzior, Tippner, Kloiber et. al.; inter alia [38, 40]	Lapped scarf joint with faces inclined	60% load bearing capacity of solid beam
2014–2018, Fajman, Máca et al.; [41–45, 50]	Scarf joints with pins or keys	
2008, Hirst, Brett, Thomson, Walker, Harris; [51]	Under-squinted butt in halved scarf with two pegs	10%
	Side-halved and bridled with two pegs	15%
	Stop-splayed and tabled scarf with key and four pegs	28%
	Face-halved and bridled scarf with four pegs	24% flexural load bearing capacity of the solid beam (in vertical bending)
2013, Mirabella-Roberti and Bondanelli [15]	Composite beam with stop-splayed scarf joints	
2012–2015, Rug et al.; [16, 17]	Model of a composite beam with stop-splayed scarf joints	Obtained load bearing capacity value—approx. 57 kN
2009, Sangree, Schafer; [52, 53]	Halved and tabled scarf joint and stop-splayed scarf joint with key	
Tensile joints		
2015–2016 Aira, Arriaga, Íñiguez-González, Guaita; [7, 55]	Halved and tabled tenoned scarf joint	The maximum tensile force was limited by the appearance of cracks and was significantly lower than the maximum value for a solid member without joints
2012, Aira, Arriaga, Íñiguez-González, Guaita, Esteban; [54]	Halved and tabled tenoned scarf joint with steel clasps or wooden pegs	
2019, Ceraldi, Costa, Lippiello; [37]	Stop-splayed scarf joint with wooden pegs or steel pins	
Adhesive joints		
2014–2015, Rapp et al.; [56–58]	Adhesive scarf joints	

technical scale made from pine wood (*Pinus sylvestris* L.) of 360 cm in length and with a cross-section measuring 12 cm × 18 cm were used. Seven different types of scarf joints were tested and compared to the reference continuous beam with the same size. With respect to the geometry of the joints, these were based on data obtained for real structures and on data from the literature. Schemes of these joints are presented in Fig. 16.
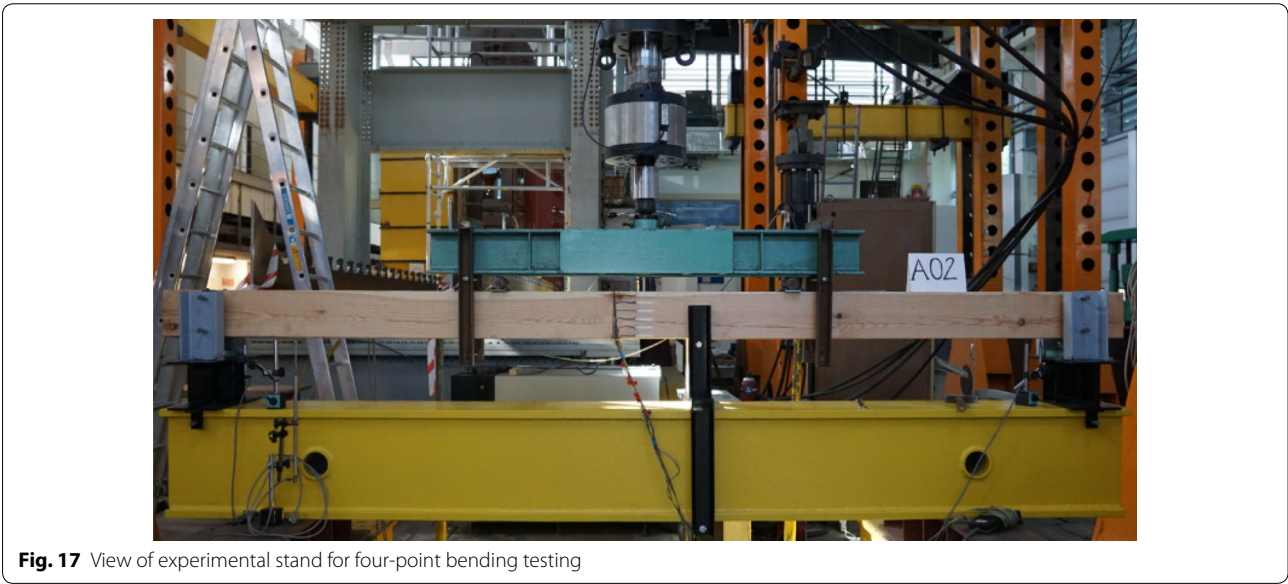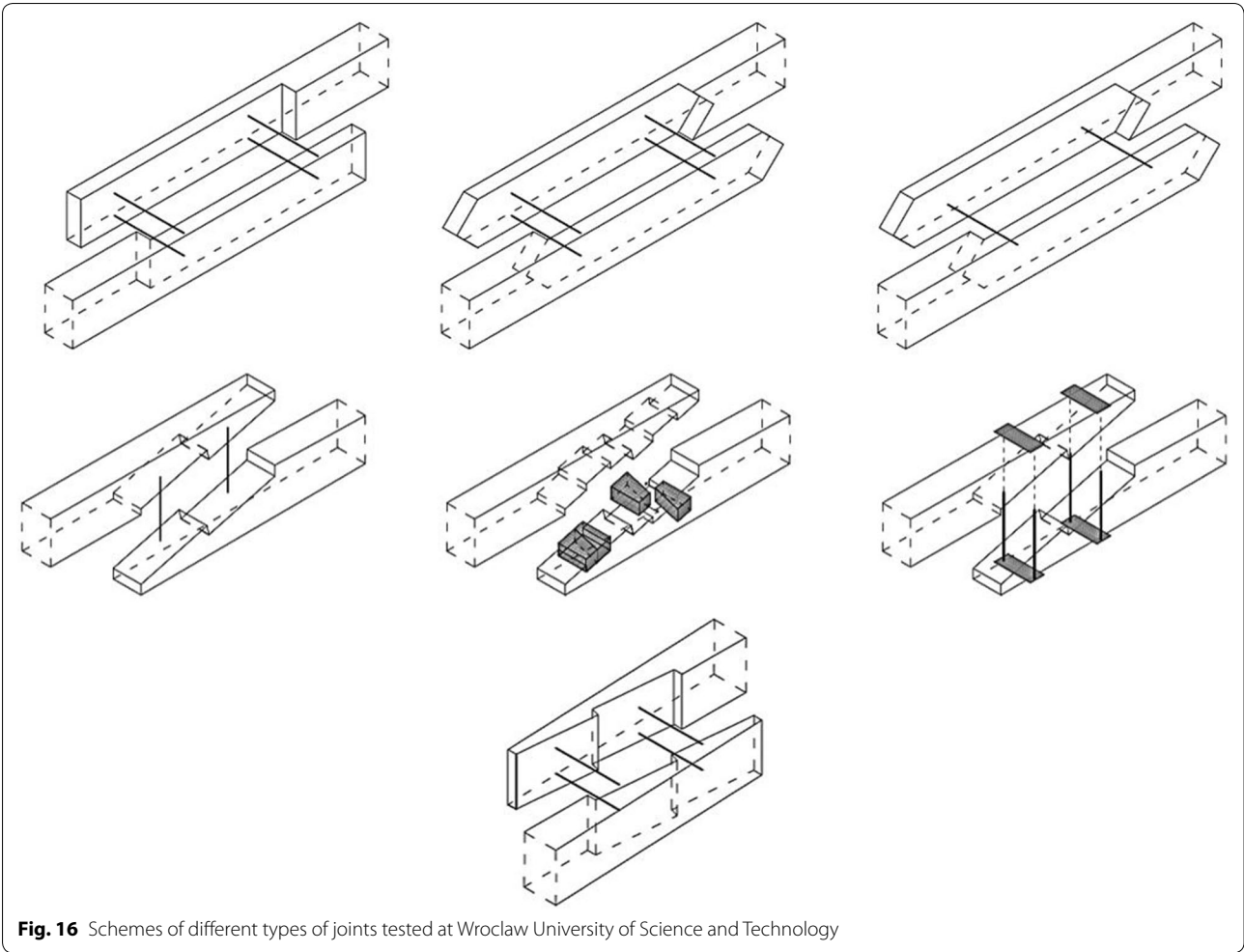
Beam models with joints were subjected to four-point bending tests, in accordance with the standard procedure. The view of experimental stand is presented in Fig. 17.

During the tests, the ultimate force was registered. Load–deflection plots (static equilibrium paths) for the beams were determined. Results for each beam series were compared to the reference beam and the stiffness parameter was determined for each joint. Moreover, simple numerical analysis will be conducted to confirm the results obtained from the experimental research.

The results and conclusions from the experimental program described above are presented i.a. in [59] and will be shown in subsequent papers.

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Table 4 Main research findings

Publication year, authors	Main findings
Flexural joints	
2014–2018, Kunecký, Sebera, Hasníková, Arciszewska-Kędzior, Tippner, Kloiber et al.; inter alia [5]	The most beneficial solution for 6 m beams in terms of load bearing capacity, stiffness and realisation is the 1.38 m long face-halved and bridled scarf joint with three pegs, located 1/5 of the length of the whole beam from the support
2014–2018, Kunecký, Sebera, Hasníková, Arciszewska-Kędzior, Tippner, Kloiber et al.; inter alia [45, 46, 49]	The greatest influence on stiffness is the angle of the inclined face in the joint. The vertical location of the pin and its dimensions have a smaller influence
2014–2018, Kunecký, Sebera, Hasníková, Arciszewska-Kędzior, Tippner, Kloiber et al.; inter alia [38, 40]	For flexural and compressed elements (e.g. rafters), a better solution is a lap joint with an angle of inclination of 60°, whereas for flexural and tensile elements (e.g. framing beams) a much better solution is a lap joint with a 45° inclining face
2014–2018, Fajman, Máca et al.; [41–45, 50]	In most cases, the deciding factor for these elements turns out to be the serviceability limit state. Joints with two and four pegs appear to behave in the same way
2008, Hirst, Brett, Thomson, Walker, Harris; [51]	The largest stiffness was observed in the case of side-halved and bridled joints in the horizontal face and stop-splayed scarf joints where there is vertical bending
2013, Mirabella-Roberti and Bondanelli; [15]	The places where the stress concentrations would likely occur are located especially near to the joint edges
2012–2015, Rug et al.; [16, 17]	Load bearing capacity in bending for teethed beams can be calculated on the condition that the value of the modulus of displacement of the tooth joint is known
2009, Sangree, Schafer; [52, 53]	Stiffness of the joint is low when compared to the stiffness in an equivalent solid beam
Tensile joints	
2015, Aira, Arriaga, Íñiguez-González, Guaita; [7, 55]	Failure modes observed: compression parallel to the grain in the notch area, shear parallel to the grain in the heel surface and cracking starting in the reduced cross-section
2012, Aira, Arriaga, Íñiguez-González, Guaita, Esteban; [54]	Proposed strengthening methods (steel clasps or wooden pegs) turn out to be equally effective in the case of halved and tabled tenoned scarf joints
2019, Ceraldi, Costa, Lippiello; [37]	A 41% increase in stiffness was observed for joints with pegs and a 52% increase for joints with steel pins
Adhesive joints	
2014–2015, Rapp et al.; [56–58]	Adhesive joints characterised by a low joint displacement between two elements made from the same material and of the same thickness were found to transfer forces in the same or similar way as in a solid element

Fig. 16 Schemes of different types of joints tested at Wroclaw University of Science and Technology

Fig. 17 View of experimental stand for four-point bending testing

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