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EXPERIMENTAL INVESTIGATIONS ON TIMBER STEP JOINTS DETERMINING THE INFLUENCE OF INTENTIONALLY PLACED INACCURACIES ON THE LOAD-BEARING BEHAVIOUR

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ABSTRACT: Various circumstances can lead to inaccuracies in timber step joints. Deviations from the desired geometry can be found for example due to inaccuracies within production or changes in the ambient humidity. The predominant question when considering step joints is, to what extent the load-bearing behaviour is influenced by these inaccuracies. To answer this question, the influence of purposefully placed inaccuracies on the load-bearing behaviour was investigated. The determined stiffnesses of the joint design with the intentionally placed inaccuracies were subsequently used within a numerical investigation in order to assess the influence on the deflection of an entire truss system.

KEYWORDS: Timber Joints, Step Joints, Carpentry Joints, Structural Engineering

1 INTRODUCTION

Large-scale prefabrication of components up to entire building sections plays an increasingly important role in the current timber construction industry. This manufacturing approach considerably reduces the on-site construction time. In order to ensure an efficient process on the construction site, a high fitting and dimensional accuracy of the elements is essential. Various methods exist for the connection of the truss components, with the most common being slotted-in steel plates in combination with steel dowels or glued-in threaded rods. In addition to these, carpentry joints can be used as a more environmentally friendly alternative. Step joints are, for example, often used in carpenter-based timber constructions or can be found in historical roof structures. They are characterised by their ability to reliably transfer compressive forces from one component to the next at different angles (between 30 and 60°) via contact surfaces [1,2]. When using timber as a building material, however, inaccuracies can occur for various reasons. Whereas in the past the carpenter's craftmanship was decisive for the production of a precisely fitting joint, nowadays, with modern CNC systems, work preparation including modelling, the creation of machining data and the conscientious work of the machinist play the most important role. Due to the permissible tolerances (-2 to +4 mm for cross-sectional dimension of > 100 and < 300 mm) according to ÖNORM EN 336:2013 11 15 [3], deviations in the cross-sectional dimensions between design and execution may occur when structural timber is used. This deviation from the nominal geometry requires a well-considered positioning of the components in the joinery process in order to ensure the best possible fitting accuracy of the connection. This is illustrated in Figure 1 in case of a double-step joint, with the inaccuracies cumulating when the positioning of the joint member is not considered during production.

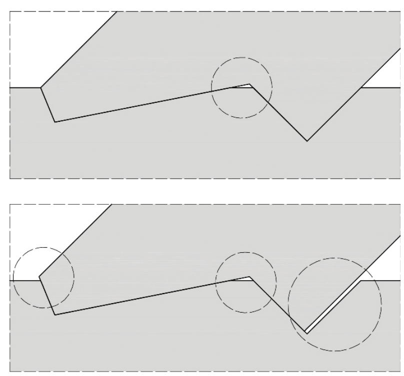

Figure 1: *Influence of the positioning of the joint's components in the joinery process on inaccuracies in case of deviation between nominal and actual cross sections using the example of the double step joint. Expected cross-sectional dimensions 120/120 mm, real cross-sectional dimensions 118/118 mm. Top: favourable positioning, bottom: unfavourable positioning.*

Apart from the dimensional inaccuracies due to the permissible tolerances, adjustments in the moisture content often lead to changes in geometry, which also result in gaps in the joints due to the different degrees of tangential and radial (regarding the annual rings) shrinkage. In order to prevent inaccuracies due to swelling and shrinkage, Blaß et al. [4] recommends that the moisture content of the components during the joining process corresponds to that in the final state.

Connections with mechanical fasteners, such as slotted-in plates and dowels show a slip at the beginning of the

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force-displacement curve due to the required hole clearance, with the standardised calculation approach for the stiffness found in [5]. According to Seim [6], the slip at the beginning is also usually seen in carpentry joints resulting from inaccuracies, elastic and plastic deformations under load as well as creep and shrinkage deformations. The schematic load-bearing behaviour of a resilient joint is depicted in Figure 2. Initially, the joint cannot transmit any load until it transforms into a perfect fitting connection. After overcoming the initial phase, a linear-elastic behaviour is observed, defined by the stiffness C in N/mm, followed by the non-linear range with decreasing stiffness.

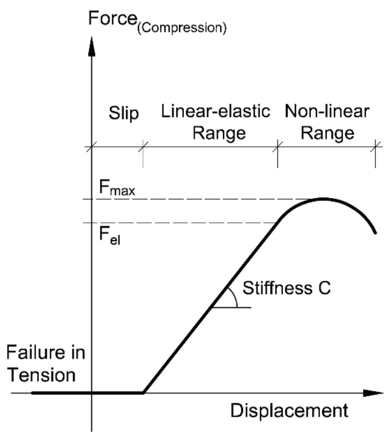

Figure 2: *Schematic force-displacement behaviour of timber step joint with diminished stiffness following [6].*

When modelling timber step joints, it should be noted that only compressive forces can be transmitted. directly under tension as timber steps are not able to transfer any tensile loads. Seim [6] states that the value for the step joints stiffness C defined at 20-25 kN/mm and the simplification of the force-displacement relationship, by disregarding slip and assuming linear-elastic behaviour until failure (see Figure 2), provide sufficiently accurate results for an implementation in practice. This statement will be assessed within this paper.

Numerous publications deal with the load-bearing behaviour of carpentry joints [7–10]. Villar-Garcia et al. [11] suggest adding a gap in the front notch of a double-step joint to improve the load-bearing behaviour. In order to achieve an efficient load transfer when using step joints, a high fitting accuracy is generally assumed as a predisposition, an assumption that has however not yet been quantified in detail. This paper therefore deals with experimental investigations of timber joints with intentionally placed gaps in step joints to determine the influence of inaccuracies on the load-bearing behaviour. The results of the experimental investigations are discussed based on recalculations of realistic truss structures.

2 Experimental Investigations

The load-bearing behaviour of traditional and newly developed step joints with a perfect fit was investigated and compared in a previous publication of the authors [2]. The most relevant geometries for practical application, as depicted in Figure 3, were selected from [2] for the investigations presented within this paper and in [12] in order to determine the influence of inaccuracies on the load-bearing behaviour. Configuration A represents a classic carpentry joint, the double-step joint. For Configuration B a third step was added to the double step joint. Geometry C is a multi-step joint with increasing cutting depth t_v from the front to the rear notch resulting in multiple shear planes. A multi-step joint with seven steps and a single shear plane was also considered within Configuration D. The reference configurations were designed and fabricated with an ideal fit between the joint members to ensure comparability with their related inaccurate versions.

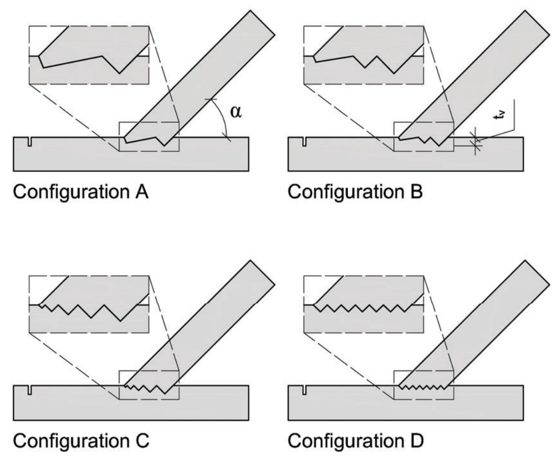

Figure 3: *Illustration of the reference configurations with a perfect fit based on the findings of [2].*

2.1 Test Specimens and Inaccuracy Placement

The investigated configurations, including the placement of the gaps, are pictured in Figure 4. While five different placements of inaccuracies were investigated for Configuration A, only one or two different variations of Configurations B, C and D were assessed. As was the case for the reference configurations and described in more detail in [2,12] the specimens were made from glue laminated timber made from spruce (GL24h) with an intended cross section of 120/120 mm (the actual cross section being 118 L3s configuration (39 l-40 w-39 l) according to ÖNorm EN 14080:2013 [13]) with the joining interfaces milled using the industrial robot at the BOKU robot laboratory [14]. All test specimens were stored in the same environment to ensure comparability of the results. The moisture content was determined using a GANN Hydromette BL H40/HT70 and lied in the required range of 12%.

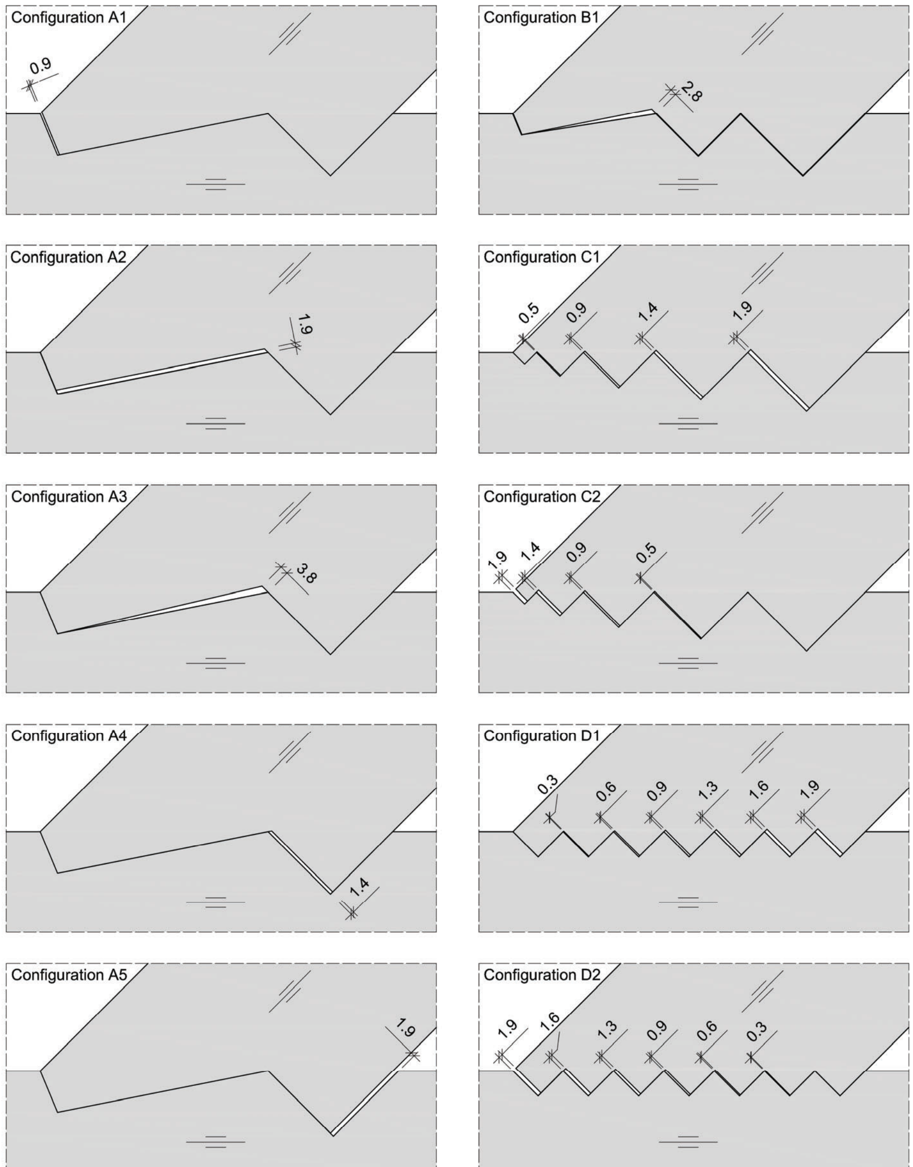

Figure 4**:** *Placement of the internally manufactured gaps in the geometries selected from [2] [mm].* ***Configuration A1****: Inaccuracy at the front of the front notch;* ***Configuration A2****: Inaccuracy at the back of the front notch;* ***Configuration A3****: Inclined inaccuracy at the back of the front notch;* ***Configuration A4****: Inaccuracy at the front of the second step;* ***Configuration A5****: Inaccuracy at the back of the second step ;* ***Configuration B1****: Inclined inaccuracy at the back of the front notch;* ***Configuration C1****: Increasing gap sizes from the front to the rear notch;* ***Configuration C2****: Decreasing gap sizes from the front to the rear notch;* ***Configuration D1****: Increasing gap size from the front to the rear notch;* ***Configuration D2****: Decreasing gap size from the front to the rear notch. [12]*

2.2 Test Setup

The test setup, described in more detail in [2,12], consisted of three steel profiles, welded together at an angle of 45°, as presented in Figure 5, allowing a vertical load application to the specimens. The length of the fore wood was set to 315 mm to achieve compression instead of brittle failure due to shearing of the tie-end.

The load, measured by a load cell, was applied using a servo-hydraulic testing machine in a monotonic, displacement-controlled manner with 1mm/min. During the tests the deformations on the surface of the specimens were recorded using digital image correlation (DIC). In postprocessing a virtual inspect extensometer, as depicted in Figure 5**Fehler! Verweisquelle konnte nicht gefunden werden.**, was used to determine the deformations between two reference points. By linking the measurement data of the load cell to the evaluated changes in length, the load-bearing behaviour was

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visualised by means of the subsequently presented force-deformation diagrams.

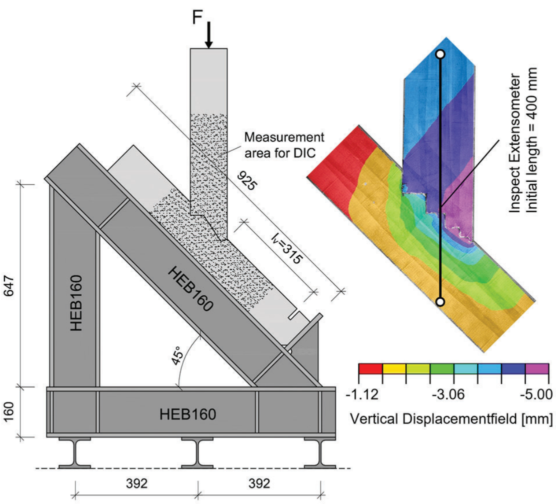

Figure 5: *Test setup including a visualisation of the virtual inspect extensometer in postprocessing. [12]*

2.3 Results and Discussion

The results of the experimental investigation of the in total 42 specimens, which were all carried out until failure, are presented in detail in [12] and illustrated in Figure 6. Within this paper the results are briefly discussed with a focus set on the stiffness C of the investigated joints. Within [12] the stiffness C is referred to as k_{lin}, which is calculated within the linear-elastic range. Apart from the mean values (MV) out of three specimens of the resulting stiffness C, Table 1 lists the mean ultimate load F_{max} for all configurations.

Table 1: *Mean stiffness C and ultimate load F_{max} values with the results of the reference geometries highlighted in bold and the lowest stiffnesses of each configuration underlined. [12]*

Configuration	F_{max} [kN]	C [kN/mm]
A1_MV	175.30	90.4
A2_MV	154.37	89.1
A3_MV	148.27	96.7
A4_MV	143.40	62.2
A5_MV	133.16	74.6
A6_MV	**165.40**	**87.0**
B1_MV	151.39	92.5
B2_MV	**171.26**	**93.9**
C1_MV	160.36	70.2
C2_MV	164.36	62.7
C3_MV	**175.30**	**93.8**
D1_MV	157.16	57.7
D2_MV	160.45	53.5
D3_MV	**176.83**	**107.5**

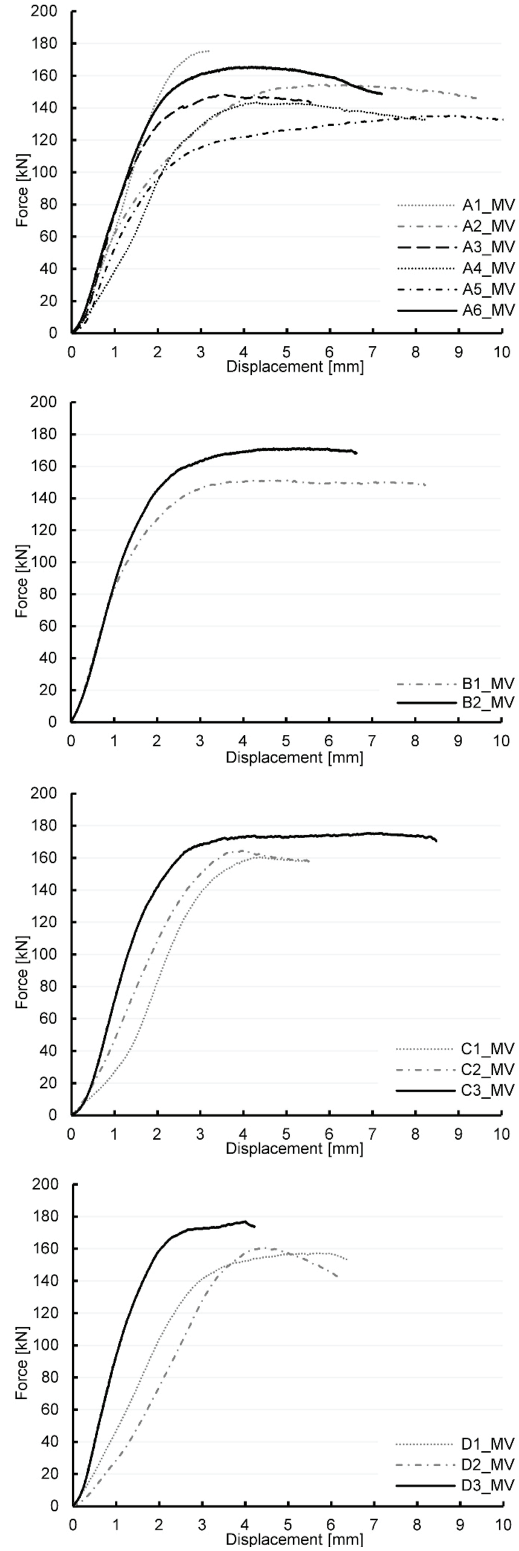

Figure 6: *Force-displacement diagrams of the mean values MV (consisting of three specimens per configuration, except for Configuration B1 with two specimens due to technical problems in postprocessing) of the individual configurations, the solid line represents the reference geometry. [12]*

The results show that, apart from Configuration B1, the intentionally manufactured gaps lead to a significantly lower stiffness C. Even though Configuration C2 shows smaller displacements, the ultimate stiffness C is lower than that of Configuration C1 and is therefore considered within the further investigations.

It could be shown that in all cases inaccuracies reduce the range of the linear-elastic phase, which starts at the end of the initial non-linear phase and ends with the beginning of failure and is characterised by a decrease in stiffness. A detailed description how these points are determined can be found [2,12]. As the linear-elastic range is reduced, the serviceability of a timber structure is negatively influenced for individual configurations if a load level above the linear-elastic range is reached in the static proof in the ULS. In only one out of ten configurations, the load-bearing capacity was increased compared to the reference geometry without gaps. Figure 7 illustrates the individual ranges according to Figure 2 and shows that the reference configurations (highlighted in bold) provide the widest range of the linear-elastic phase.

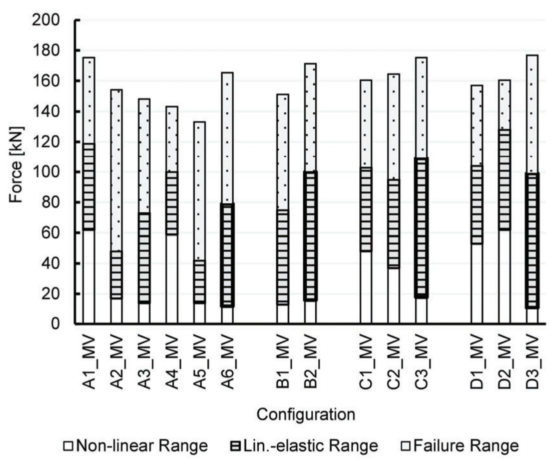

Figure 7: *Observed ranges of the mean values MV of the individual configurations. [12]*

In postprocessing, no damage was detected on the surface of the specimens at the end of the linear phase as determined in [12], so that a hypothesis of a local compression failure of the fibres leading to the stiffness decrease was made. The stiffness C of a single-step joint investigated in [2] was calculated to be 24.84 kN/mm according to [15], lying within the previously mentioned specified range of 20-25 kN/mm according to [6]. The results of the experimental investigations, however, show a stiffness C in the linear-elastic range of 53.5-107.5 kN/mm, as listed in Table 1. Even though the slip and initial non-linear range is not considered in the stiffness according to [6,15] it is still significantly lower than the determined values. This shows that the assumption of a purely linear-elastic response of a step joint with the stiffness according to [6] lying in a rage of 20-25 kN/mm should be seen as rather conservative with the authors advising to at least consider the initial non-linear range in a bi-linear approach.

In regard to the failure modes, a detailed discussion can be found in [12], where the DIC measurements and the thorough documentation of all surfaces allowed for a definition of seven predominant failure modes. Summarising the results, no general valid statement can be made on the relation of the force at the onset of the individual failure modes and the end of the linear-elastic range with the intentionally placed gaps not resulting in the avoidance of specific failure modes.

3 Practical Application

A typical application of step joints is the connection of the compression struts to the chords in trusses. In order to investigate the influence of the previously determined stiffness decreases within the joint areas caused by the inaccuracies in the connections on the overall deflection behaviour of an actual structure, the behaviour of a symmetrical parallel chord truss, as pictured in Figure 8, was determined for various joint stiffnesses using the Software RStab by Dlubal [16]. This study focuses exclusively on the analysis of the influence of inaccuracies within the joint between the connected truss members. Other parameters that additionally influence the deflection behaviour, such as deviations in strut length or joints position, were not considered.

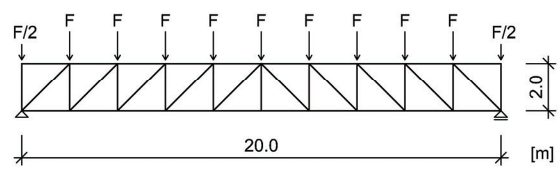

Figure 8: *Illustration of the investigated parallel chord truss.*

The truss was designed with a span of 20 m and an overall height of 2.0 m with a declared strength class of GL24h for all chord and strut elements. As would be the case within the actual construction, the top and bottom chords were modelled as continuous beams with a cross section of 120/200 mm. The vertical truss members were modelled as two 60/120 mm cross sections placed at the outer sides of the chords, while the diagonal struts, subjected to compression, were chosen as in the experimental investigations with a cross section of 120/120 mm.

The considered load cases were the dead weight, a load from a possible superstructure (permanent) and snow (variable). The loads of 7.0 kN and 4.8 kN, respectively, were applied to each node of the top chord and resulted in the maximum utilisation (0.99) of the structure (in particular the diagonal strut near the support) within the ultimate limit state (ULS) according to [5]. The normal forces under the serviceability limit state (SLS) characteristic load combination are presented in Figure 9.

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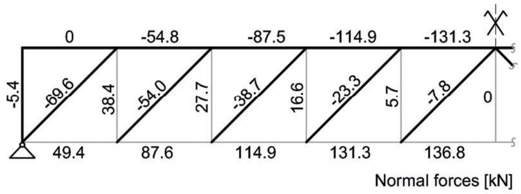

Figure 9: *Normal forces [kN] in the individual truss members (characteristic serviceability limit state SLS load combination).*

In order to make a statement in regard to the influence of inaccuracies of the step joints on the deflection of the entire truss system, the determined load-bearing behaviour from the experimental investigations was implemented within the RStab model. The stiffest and the most ductile connections of each configuration were chosen for a direct comparison, with the reference geometries always being the former and the latter being the configuration underlined in Table 1, resulting in a comparison of Configurations A6 and A4, B2 and B1, C3 and C1 as well as D3 and D2. In addition, the deformations of a truss structure with pin-joints (rigid joints with frictionless nodes) was calculated. The mechanical joint-properties of the compression struts based on the experiments were approximated within the model based on the determined load-bearing behaviour using a multi-linear modelling approach as presented in Figure 10. The kinks within the approximation were set at the end of the non-linear range, at the end of the linear-elastic range and at the point of the maximum force with their corresponding deformation followed by a constant plateau. The calculation was rounded off with the evaluation of a system with a compression joint stiffness C of 20 kN/mm, as defined by Seim [6], and a tensile joint stiffness C of 25 kN/mm using ring connectors for two shear planes with a diameter of 65 mm according to [17].

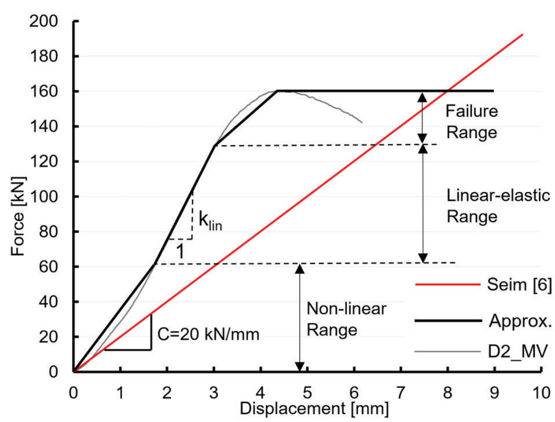

Figure 10: *Illustration of the multi-linear approximation of the load-bearing behaviour in the modelling process of Configuration D2_MV and the linear-elastic behaviour according to Seim [6].*

The results of the numerical investigations are presented in Table 2. It must be mentioned, that within the calculations only the instantaneous deformations w_{inst} were considered and the additional deflections caused by creep where neglected.

Table 2: *Maximum deflection in mid span for the serviceability limit state SLS with the reference geometries highlighted in bold.*

Configuration of compression strut	Maximum deflection in mid span [mm]
Pin-joints	32.9
With C=20 kN/mm according to Seim [6] (compression) and C=25 kN/mm (tension)	66.8
A4_MV	52.5
A6_MV	**48.3**
B1_MV	46.7
B2_MV	**47.3**
C1_MV	55.5
C3_MV	**49.2**
D2_MV	55.3
D3_MV	**46.5**

The results show that the stiffness C of the joints has a significant influence on the deformations when cumulating them over an entire truss structure. As expected, the system with pin-joints and the system with the stiffness defined by Seim [6] represent the upper and lower limits of the assessed systems, with the rigid system showing less than half of the deflection of the other. When considering the deflection w_{inst} without consideration of creep, a limit of l/300 according to [5] is set at 66.7 mm, which is slightly exceeded by the conservative assumptions of Seim [6].

It must be noted that the present study did not use variable cross sections for the compression struts, as this is also often not the case in practice (higher effort in design and execution). The chosen design, however, leads to various load levels within the struts, with the highest being - 69.6 kN at the supports, with a maximal utilisation, and the lowest being in the middle with -7.8 kN and low utilisation. By prestressing the connection, by for example a superelevation of the truss [18], the load level in the minimally utilised struts can be raised resulting in a load-bearing behaviour with a maximum stiffness. The prestressing would also eradicate the effects of the undesirable inaccuracies by counteracting the initial non-linear range, before any external load is even applied.

The present numerical investigation further shows that the most unfavourable positioning of inaccuracies (Configuration A4) within the double-step joint entails a 9% increase of the total deflections of the structure compared to the reference geometry (Configuration A6) and a 60% increase compared to the truss model implementing pin-joints. The investigated load level was not sufficient to use the potential in terms of the linear-elastic range of the more efficient reference geometry B2. The required load within the joint should lie between 75 (end of linear-elastic range B1) and 100 kN (end of linear-elastic range B2) to exploit the potential of B2 compared to B1 in terms of minimising the deflections. It has to be mentioned, however, that this load level cannot be reached for the given cross section within the static proof in the ULS according to [5] for the given cross section and thus represents a theoretical approach. A noticeable increase in deflection is noticed for both Configurations C3 and D3 compared to their reference geometries with 13% and 16%, respectively.

4 CONCLUSION

With the deflection of timber constructions, especially trusses, essentially depending on the stiffness of the joints, the presented investigations are of high scientific value. Within this paper the influence of intentionally placed inaccuracies on the load-bearing behaviour of step joints is presented. The initial goal of this study was to investigate if specific placements of gaps within joint could influence the failure mechanisms or harbour benefits in regard to the load-bearing behaviour. Four different configurations of multi-step joints were produced and tested in experimental investigations with various inaccuracies and compared to perfect fit reference geometries. The results show that the load-bearing behaviour is negatively affected by inaccuracies with stiffness and load-bearing capacity decreases of up to 16% and 19%, respectively. Furthermore, the individual ranges of the load-bearing behaviour depend on the position of the gaps and show a predominantly negative influence, with a perfect fit critical for the highest possible stiffness in the connection and smallest possible deflection of an entire truss structure. If pin-joints are considered within dimensioning for example by using a FE software the deflection is significantly underestimated, while stiffness estimations from literature, e.g. Seim [6], show rather conservative results with higher deflections than can be expected in reality (without a consideration of creep).

As an endnote it should be mentioned that the use of multi-step joints does not provide any significant advantages considering the deflection of entire systems when compared to the traditional double-step joint.

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