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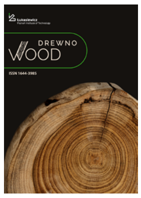

Improving the Stiffness of the Corner Connections in Wooden Door Frames

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Research was carried out to determine the strength and stiffness of corner joints in interior door frames, depending on their construction and on modifications made to their design. Initially, two models were compared: model 1, with two connectors using a clamping screw at an angle of 45°, and model 0, with a single connector using a cam joint at an angle of 90°. In all tests, model 1 exhibited significantly better mechanical properties. To improve the performance of model 0, three alternative construction models (A, B, and C) were proposed by changing the position of the door frame mounting holes. In the compression test, model A achieved an increased bending moment compared to model 0, while models B and C showed no such improvement. In the tension test, the bending moment values remained at a similar level across all construction variants, including model 0. In terms of bending moment, the best result in compression was achieved by model A (48.26 Nm), and in tension by model B (48.72 Nm). The highest stiffness was demonstrated by model 1 (up to 42.38 kNm/rad), while among the alternative models, model C achieved the best result in tension (33.98 kNm/rad). Due to the favourable increase in bending moment under compression in model A and the insignificant changes under tension across all variants, model A is considered the optimal solution. To enhance the strength of the door frame, offset holes can be applied as proposed in this model.

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Introduction

Interior doors consist of a door frame and a door leaf, with their construction typically made of wood-based materials. Owing to their outstanding properties and aesthetic appeal, such doors are highly valued by consumers, designers, and building developers. Consequently, they are extensively utilized in a wide range of buildings, including residential, office, hotel, educational, and healthcare facilities (Lao et al., 2023). The variety of internal door types has increased due to advancements in production technologies, and manufacturers are paying more and more attention to the use of advanced production technologies to increase efficiency and meet the needs of consumers (Kwidziński et al., 2023; OB-RPPD, 2023; Pędzik et al., 2020).

The most common are internal door frames that enable quick assembly. The door frame is installed by assembling the frame structure horizontally (as a frame) and then placing it in a ready-made opening in the wall and mounting it with assembly foam. When placing the frame in the opening, it is difficult to maintain its rigidity, and so it is at this time that the angle connections are subjected to the greatest loads. The angle connections in the door frame are designed to transfer loads. This method of installation, unfortunately, causes the risk of mechanical damage to these connections when the door frame is placed in building openings. When using door frames, the main factors affecting their durability are the material from which they were made and the assembly foam used to install them. However, in the case of heavily used doors, the assembly foam's properties deteriorate. In this situation, the angle connections in the door frame begin to affect the maintenance of the door frame in the correct position and the operation of the door. The strength of the connections in these frames depends on the strength of the angle connection used. Connections with insufficient rigidity can lead to deformation of the connectors, which in practice causes the formation of unsightly gaps between frame elements, reducing the aesthetic value of the product and its mechanical strength. During assembly, bending moments most frequently develop in corner joints under both compression and tension loads. From a technical point of view, a stiffer connection will provide a more precise connection of the frames. This makes the place of contact of the individual elements less visible, and it is easier to place a stiffer frame in the opening and maintain the correct dimensions between the vertical frames, thus facilitating more precise assembly.

In building joinery, tests have been conducted on the strength of frame structures. In one study (Simić et al., 2023) the effect of humidity changes on the strength of the frame connection of the window sash was analysed. Its authors also indicated the lack of official standards specifying the strength of the frame structure joint in building joinery, using the example of window frame tests. When considering door frames, there is also a lack of standards regulating the strength of connections of door frames made of wood-based materials. In wooden or wood-based structures, numerous tests of angular connections have been conducted, considering different materials (Krzyżaniak et al., 2021) or different types of connections (Altun, 2010; Karaman, 2021; Kasal et al., 2023; Skorupińska et al., 2021).

Various studies have explored materials and joint configurations to enhance door frame stiffness and load-bearing capacity. This research has highlighted the importance of material selection and connector type in determining the stiffness of wooden door frame corners. Birch plywood and glulam elements connected with self-tapping screws have been shown to provide satisfactory linear loading stiffness, with failure modes predictable through analytical models (Wang et al., 2024). Glued-in hardwood dowels in plywood frame corners improved bending capacities, and design models are available for calculating joint strength and rotational stiffness (Jensen et al., 2002). The diameter of dowel holes and the spacing between dowels significantly affect the tensile strength of oblique corner joints, with double dowels providing greater strength than single dowels (Hu et al., 2023).

Mechanical connectors like bolts and pins are commonly used in timber frame connections. However, modern connectors can improve load capacity and rigidity, simplify assembly, and enhance performance (Branowski et al., 2020; Johanides et al., 2020). Adding metal straps or OSB sheathing, especially in combination with high-density wood products, increases the bending moment resisted by corner joints (Demirel et al., 2024; Demirel and Sen Er, 2022). Further enhancement can be achieved by applying fibre-reinforced polymer (FRP) (Yerlikaya, 2014, 2013). While these studies provide valuable insights, it is crucial to consider the impact of the placement of the joints on the door frame's overall stiffness.

This study actively evaluated how multiple types of connections and several structural changes significantly affect the load-bearing capacity of the casings during both the installation process and their usage over time. By concentrating on developing design solutions, the results make it possible to improve the durability, stiffness and ease of installation of interior door casings while also ensuring that their aesthetic and functional qualities remain intact. The study aimed to determine the strength and stiffness of corner connections in the frames of interior door casings, depending on their design and modifications made to the construction of the frame joints. The stiffness and strength of selected door frame structures were analysed in the form of composite door frame corner samples. In this study, two loading models – compression and tension – were preferred as a test method for determining the strength and stiffness of door frame corner joints.

Materials and methods

Diagonal compression and tension tests of the corner joint samples were performed on a numerically controlled Zwick 1445 universal testing machine (Zwick Roell AG, Ulm, Germany) with a capacity of 10 kN, at a loading rate of 10 mm/min under static load. For the tension tests, the bottoms of both corner joint frames were placed on elements with rollers at the bottom and a base notch at the top, allowing the sample to move outward during loading. For the compression tests, the frames were placed in fixtures with axial load movement. During the compression and tension tests, the maximum forces F (N) were measured to the nearest 0.01 N, and the deflection in the direction of the acting force DF (mm) was determined to the nearest 0.01 mm. The loads were increased at a rate of 10 mm/min. The test ended when the force dropped by 200 N or the displacement reached 20 mm. From each frame variant, 10 samples of the angle connection were prepared (5 for tension and 5 for compression). A total of 50 samples were tested (25 for tension, 25 for compression). The results were then analysed to calculate the strength and stiffness of the angle connections. The position of samples during the compression and tension tests is shown in Fig. 1.

The bending moment capacity of the connections in compression (MC) and tension (MT) were calculated using equations 1 and 2:

$$MC = F Lc' \ (\mathrm{Nm}) \quad (1)$$

$$MT = 0.5 Lt' \ (\mathrm{Nm}) \quad (2)$$

where:
F is the maximum force acting on the corner of the frame [N],
Lc' and *Lt'* (mm) are the length of the arm of force for compression and tension, respectively. The values are *Lc'* = 148 (mm) for compression and *Lt'* = 134 (mm) for tension.

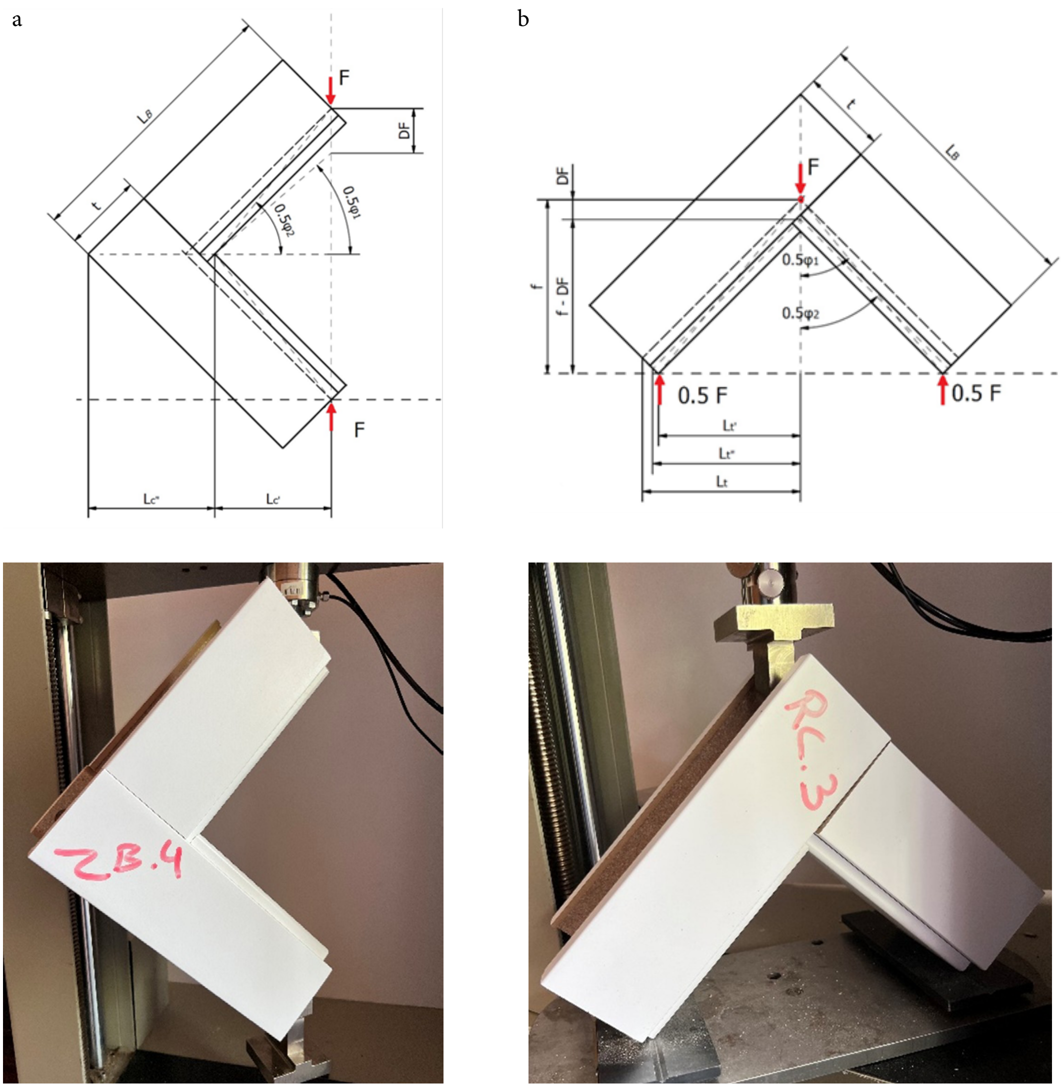

Fig. 1. Samples being tested on a testing machine: a) compression test, b) tension test

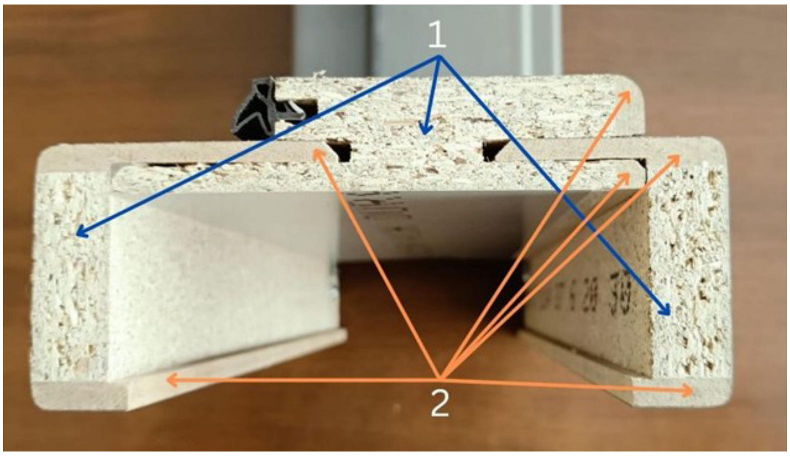

Fig. 2. Construction of the door frame:1 – particleboard, 2 – HDF

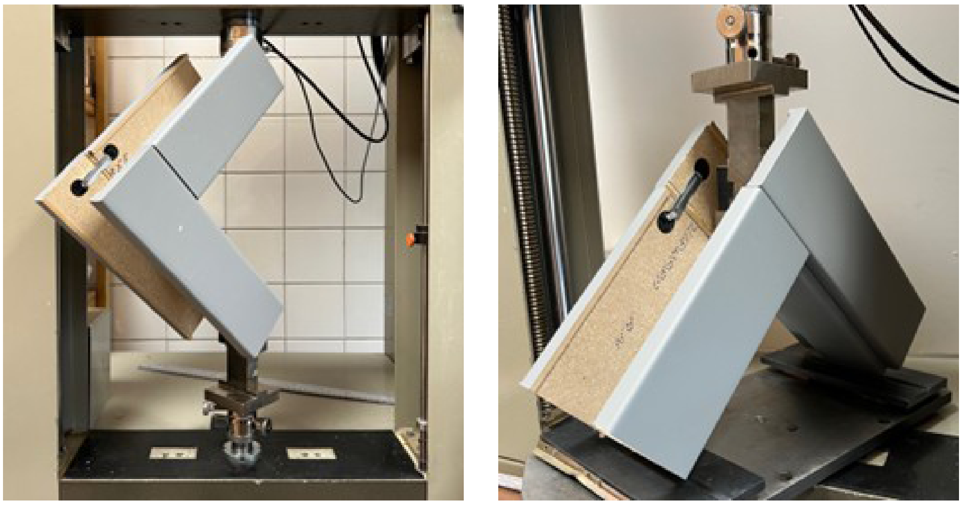

Fig. 3. Sample of construction model 0 – door frame with a connection at 90°: a) compression test, b) tension test

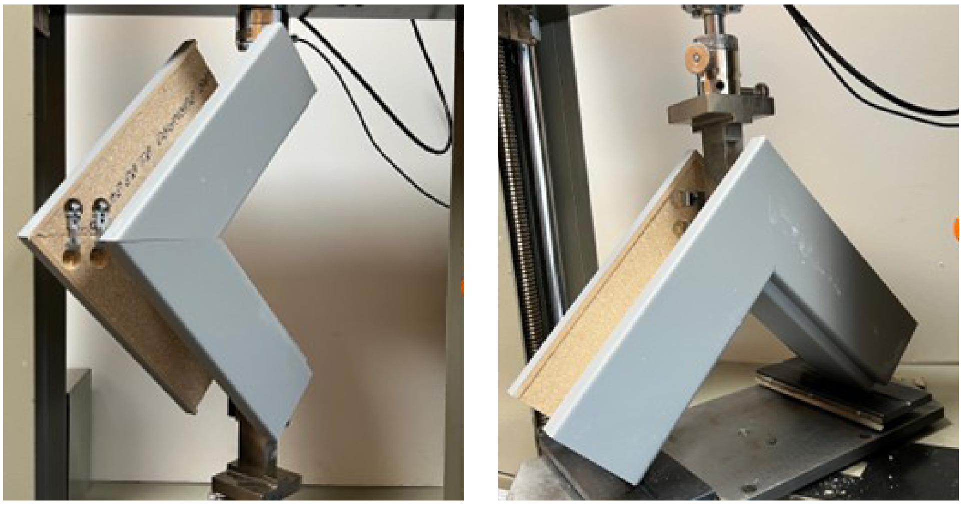

Fig. 4. Sample of construction model 1 – door frame with a connection at 45°: a) compression test, b) tension test

The stiffness values of the corner connections were then calculated as the quotient of the bending moment MT, MC and the corresponding decrease or increase in the angle φ between the vertical and horizontal elements of the door frames. These angles were determined based on the measurement of the deflection DF caused by the external load, and deformation angles were determined. The stiffness coefficients for compression KC (equation 3) and tension KT (equation 10) for the connections are calculated according to the following equations 4–9 and 11–14:

$$KC = FLc'/\varphi \quad (3)$$

$$\varphi = (\varphi 2 - \varphi 1) \quad (4)$$

$$Lt' = \sqrt{2}(LB - t)/2 \quad (5)$$

$$0.5\varphi 1 = atg\ (Lt'/f) \quad (6)$$

$$0.5\varphi 2 = a\ tg\ (Lt''/f) \quad (7)$$

$$f = Lt' + (\sqrt{2}/2)\ t \quad (8)$$

$$Lt'' = \sqrt{Lt'\ 2 + f2\ - (\ f - DF)2} \quad (9)$$

$$KT = FLt'\ /\ 2\varphi \quad (10)$$

$$Lc' = (\sqrt{2}/2)LB - Lc'' \quad (11)$$

$$Lc'' = t\sqrt{2} \quad (12)$$

$$\varphi 1 = 2\ a\ t\ g\ (\sqrt{2}\ LB/2Lc') \quad (13)$$

$$\varphi 2 = 2asin((\sqrt{2}/2)\ LB - DF)/\ \sqrt{t2 + (LB - t)2}) \quad (14)$$

where:
φ is the angle between the vertical and horizontal elements of the door frame [°],
LB is the length of the supporting element [m],
t is the thickness of the frame without the door frame trim [mm].

In the first stage, tests were carried out on two different types of door frames. In one, the frames were connected at an angle of 90° (marked as model 0) as shown in Fig. 3, and in the other at an angle of 45° (marked as model 1) as shown in Fig. 4.

Both versions are standard door frames as produced to date by Porta KMI Poland. The door frames are made of glued layers of particleboard and high-density fiberboard (HDF). After assembly, the whole frame is laminated. The arrangement of individual layers is presented in Fig. 2.

In addition to the difference in the arrangement of the frames themselves, these connections also differed in the type and number of connectors. Model 1 used two connectors with a clamping screw. However, due to the construction limitations of the drilling and milling head, the minimum possible hole distance is 40 mm. This means that it is not possible to achieve a distance of 20 mm, as in model 1. For this reason, model 0 uses a single connector with a cam joint.

These tests were designed to show which door frame construction had better strength properties. The subsequent step was to identify potential directions for modifying the door frame construction and to evaluate the effect of modifications on bending moment and stiffness under tension and compression, in order to improve the frame's properties.

Statistical analysis

The statistical analysis for differences looked at two important factors: bending moment and stiffness of corner joints. The null hypothesis was that there are no significant differences in strength and stiffness among the various corner joint designs, while the alternative hypothesis stated that such differences do exist. Average values for bending moment and stiffness were compared using the t-test for two groups. The significance level is set at $\alpha = 0.05$.

The analysis includes comparisons between corner connections in the door frame at 45° (model 1) and 90° (model 0), as well as between corner connections at 90° for the combinations of models A and B, A and C, and B and C. The objective is to determine whether design modifications lead to significant differences in strength and stiffness, facilitating the selection of optimal design solutions.

Results and discussion

Analysis of the effect of door frame construction on stiffness showed that model 1, with connectors at 45°, had significantly better strength properties than model 0, with connectors at 90°, in all tests. Accordingly, alternative construction models labelled A, B and C were proposed to improve the strength properties of the joint. The changes consisted in adjusting the position of the axes of the connections' pin holes in three different configurations, shown in Fig. 5 along with model 0:

Table 1. Maximum forces in compression and tension tests of door frame samples

Model	Compression test	Tension test
	Fmax [N]	
1	687.16	811.83
0	354.58	601.77
A	475.30	562.30
B	289.88	631.37
C	305.29	504.80

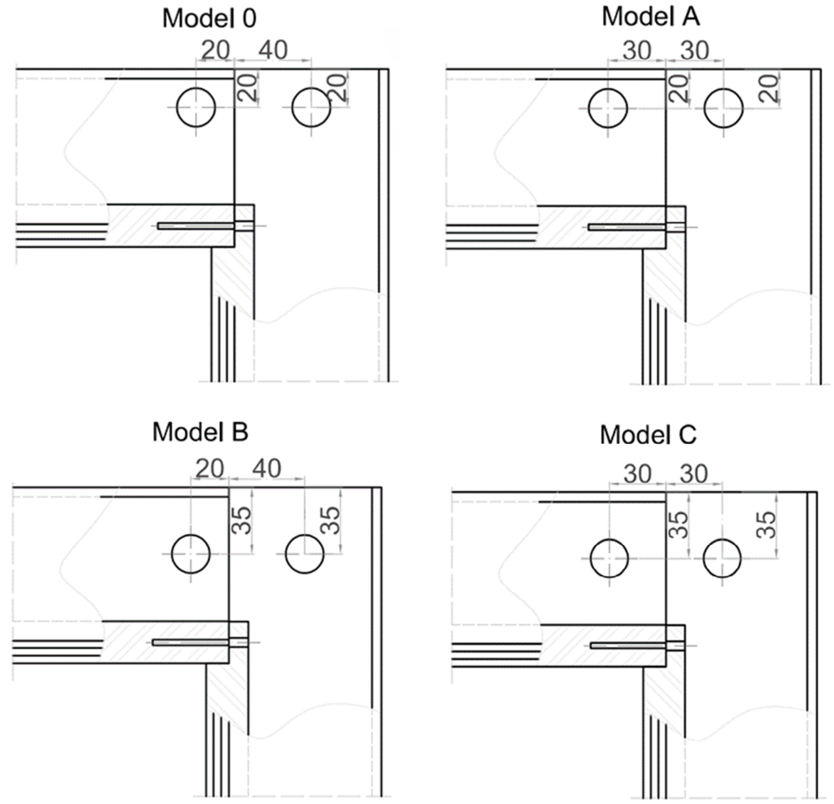

Fig. 5. Construction models with variable hole positions for connector installation, including model 0 and its modifications (A, B, C)

- model A – holes shifted in the horizontal axis by 10 mm towards the centre of the door frame,
- model B – holes shifted in the vertical axis 15 mm down the door frame,
- model C – a combination of both changes, i.e. simultaneous displacement in both axes.

The three proposed new positions of the holes for mounting the connector are shown in Fig. 5, in comparison with model 0.

This change does not affect the technological process. The same number of operations is performed; only the position is different, which is important for the efficiency of door frame production. Subsequently, new connection specimens were made according to the new specification and strength tests were carried out on the new door frame versions. Test results obtained during both stages of the tests were collected together to compare all of the tested constructions.

Table 1 shows the values of maximum forces F during compression and tension tests of the samples. The results of the compression and tension tests obtained are shown in Figures 6–7, with bending moment M and stiffness K.

Model 0 exhibited a significantly lower maximum force value than model 1, indicating its limited resistance to compression and tension loads with the connector at 90°. In terms of compression, among the alternative models for model 0, which had a value of 354.58 N, an improvement in the maximum force value was observed in model A (475.30 N). In contrast, models B and C showed even lower strength than model 0, suggesting that their geometry was not conducive to carrying compression loads. In terms of tension on the door frames, among the alternative models, the best result for tensile strength was achieved by model B (631.37 N), an improvement over model 0 (601.77 N). Model A produced a slightly lower value, indicating no significant improvement, while Model C achieved the worst result, indicating a weakening of the construction. The statistical significance of the differences in maximum force values between the tested joint configurations under compression and tension loading is summarized in Table 2.

During the compression test, a significant difference was observed between the 45-degree and 90-degree connections, as indicated by the t-test results: $t(20) = 16.892$, $p < 0.001$. The mean maximum force for the 45-degree connection (model 1) was 687.16 N, whereas for the 90-degree connection (model 0) it was 354.58 N. The 95% confidence interval for the difference in mean maximum forces ranged from 316.84 N to 347.21 N, indicating a highly significant increase in load-carrying capacity for the 45-degree connection. Given that the p-value is well below 0.05, the null hypothesis is rejected, confirming that 45-degree

Table 2. Statistical significance of differences in maximum force values between frame corner joint configurations under compression and tension loading (reference: model 0)

Comparison	Loading type	p-value	Significance
Model 1 vs Model 0	Compression	< 0.001	Yes
Model A vs Model 0	Compression	< 0.001	Yes
Model B vs Model 0	Compression	< 0.001	Yes
Model C vs Model 0	Compression	0.0039	Yes
Model A vs B	Compression	< 0.001	Yes
Model A vs C	Compression	< 0.001	Yes
Model B vs C	Compression	< 0.001	Yes
Model 1 vs Model 0	Tension	< 0.001	Yes
Model A vs Model 0	Tension	0.024	Yes
Model B vs Model 0	Tension	0.040	Yes
Model C vs Model 0	Tension	0.0051	Yes
Model A vs B	Tension	< 0.001	Yes
Model A vs C	Tension	0.0764	No
Model B vs C	Tension	< 0.001	Yes

connections exhibit significantly greater resistance to compressive loads than 90-degree connections. The t-test further revealed statistically significant differences between the various connection types for 90-degree angle connections. The mean maximum force for model A was 475.30 N, which was significantly higher than the 289.88 N observed for model B ($t(20) = 16.104$, $p < 0.001$). Additionally, model A demonstrated significantly superior performance in comparison to model C, with a mean maximum force of 475.30 N as opposed to 305.29 N, $t(20) = 14.823$, $p < 0.001$. Additionally, model C demonstrated greater strength than model B, with mean forces of 305.29 N versus 289.88 N, and this difference was statistically significant: $t(20) = -5.028$, $p < 0.001$. These findings indicate that model A is the most effective in transferring compressive loads among the 90-degree configurations.

The Welch Two-Sample t-test further revealed a statistically significant difference in mean maximum forces between 90-degree and 45-degree connections ($t(20) = 13.927$, $p < 0.001$). The mean maximum force for 90-degree connections (model 0) was 601.77 N, whereas for 45-degree connections (model 1) it was 811.83 N. The 95% confidence interval for the difference ranged from 181.32 N to 226.77 N, confirming that 45-degree connections are significantly more effective at bearing tensile loads. The t-test revealed statistically significant differences in tensile strength among the 90-degree connections. Model B demonstrated the highest tensile strength of 631.37 N, which was significantly higher than the 504.80 N observed for model C ($t(20) = 9.882$, $p < 0.001$). Furthermore, model B demonstrated a substantial enhancement in performance when compared with model A, with mean forces of 631.37 N versus 562.30 N, $t(20) = 8.211$, $p < 0.001$. However, no statistically significant difference was observed between model A (562.30 N) and model C (504.80 N), as indicated by the p-value of 0.0764, suggesting that both configurations exhibit comparable performance in tension.

In the case of the bending moment, model 0 achieved more than twice the value in compression than model 1, at 33.75 Nm, and a value of 49.42 Nm in tension. Of the alternative models, model A was the best in compression, with a value of 48.26 Nm. Models B and C produced lower values than model 0, suggesting their adverse effect on strength. In the tension test, model B scored close to model 0 at 48.72 Nm, while models A and C achieved lower values.

Again, stiffness analysis showed that model 1 had the highest value: as high as 36.87 kNm/rad in compression and 42.38 kNm/rad in tension. Model 0 exhibited a much lower stiffness, and model A obtained a value very close to it in compression (11.16 and 11.52 kNm/rad, respectively), meaning that the modification did not negatively affect this parameter. Models B and C displayed the lowest stiffness, making them the least favourable variants in terms of deformation resistance. On the other hand, among the alternative models, model C (33.98 kNm/rad) had the best result in the

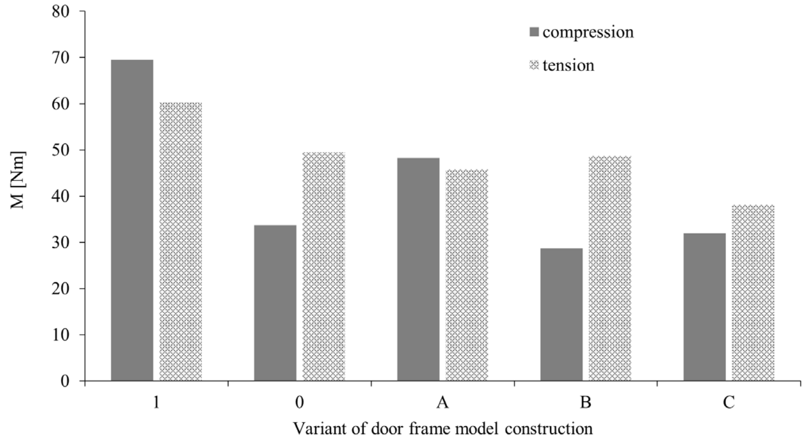

Fig. 6. Comparison of bending moment for different door frame construction models

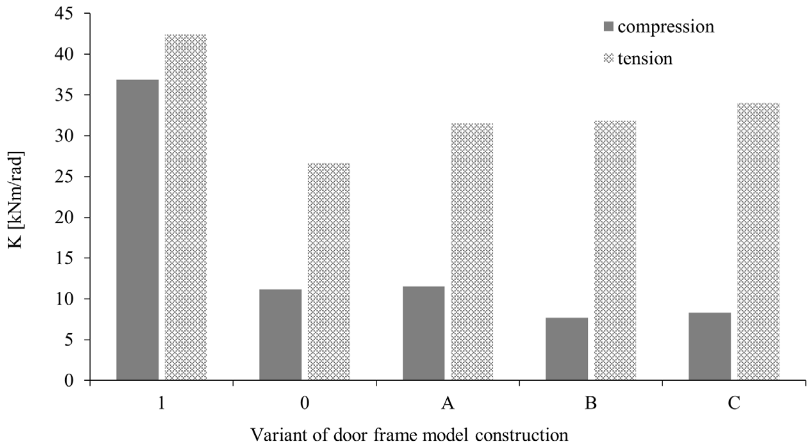

Fig. 7. Comparison of stiffness for different door frame construction models

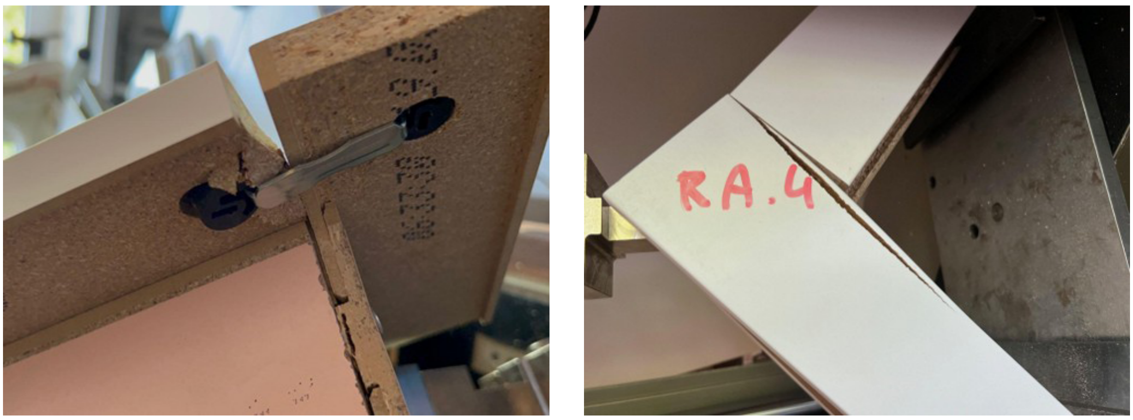

Fig. 8. Damage to door frame samples after tests

tensile test, showing an improvement in stiffness. Models A and B also improved in stiffness relative to model 0, but to a lower degree.

Considering all of the results and the identified relationships, it should be concluded that the best alternative to the base model 0 is model A. In the compression test, model A showed a significant improvement in strength (the maximum force increased from 354.58 N to 475.30 N, and bending moment from 33.75 Nm to 48.26 Nm), while maintaining stiffness at the level of model 0. In the tension test, it was model B that obtained the best results among the alternative models, but its weak compression strength means that it is not the best overall choice. Model C, on the other hand, had improved stiffness, but its results in terms of maximum force and bending moment were the weakest, ruling it out as the best choice. The differences in the results obtained were significantly influenced by the arrangement of the connectors, particularly the distance of the connector socket from the connection surface. The strength of the joints in the door frame was also observed to be influenced by the quality and density of the material used to make these structural elements. This is supported by the comparisons of the bending forces and moments values presented above.

Below are examples of damage to the tested door frames (Fig. 8).

Conclusions

An inadequate door frame strength can result in visible gaps at the joints and an unsightly appearance. The research compared five construction models, including two standard models. Model 0, with a 90° connector, achieved a significantly lower maximum force value compared with model 1 with connectors at an angle of 45°, indicating its limited resistance to compression and tensile forces.

Subsequently, three alternative models (A, B and C) were proposed, differing by a change in the construction concerning the position of the connector holes. This is beneficial for installation and usability reasons. This does not entail any change in technology, because the shape of the hole and fastener is the same; only their position changes. In the compression test, there was an increase in bending moment for model A compared to model 0, while models B and C showed no such change. Models B and C showed an improvement in tensile stiffness similarly to model A. This does not worsen the stiffness in compression, but improves it in tension, which has a positive effect on the strength of the joint. Due to the favourable increase in the compressive bending moment value in model A and the insignificant change in the tensile bending moment in all variants, model A is the optimal solution. To improve the strength properties of the door frame, it is possible to use offset holes according to this model. Based on analysis of the results, it can be concluded that model A is the best alternative to 0.

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Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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