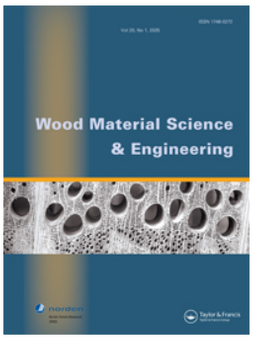

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Effect of cracks on the load-carrying capacity of glulam

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ABSTRACT

Engineered wood products (EWPs) may be prone to cracking though the impact of these cracks varies depending on the specific product. The impact of existing cracks on the structural behaviour of different EWPs is potentially detrimental in practical applications but has not been sufficiently studied. To meet the challenge, the primary objective of this study is to investigate the influence of crack length and location on the load-bearing capacity of glulam. Over 50 glulam beams with 10 different initial cracks were tested. The examined cracks were artificially induced delaminations of different lengths located in the middle of the beam's cross-section. Based on the findings, the length of the crack has an impact on the shear strength of the beam, but less than expected in the light of a simplified structural analysis that incorporates the crack into the effective width of the cross-section. Additionally, the crack length importance is connected to the stress state along the crack. The practical use of this study lies in improving the structural reliability of glulam by understanding how crack parameters affect the loadbearing capacity. As the main conclusions of the study, practical guidelines for the assessment of the load-bearing capacity of glulam with existing cracks were given.

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Glulam; crack; load-carrying capacity; cracked beam; safety

1. Introduction

Wood has been a basic construction material for centuries, evolving into engineered wood products (EWPs) such as glulam, cross-laminated timber (CLT), and laminated veneer lumber (LVL) to meet modern structural demands. The key advantage of EWPs lies in their layered construction, which minimises the impact of strength reducing wood features such as knots and fibre deviation found in solid wood. However, even in EWP, the orthotropic nature of wood and natural inhomogeneities – shaped by growth environment, conditions, and genetics – cannot be disregarded, as they significantly affect structural integrity, especially in terms of cracking under external loads and moisture changes. For example, at the locations of knots, the grain direction deviates from the primary orientation, which increases the likelihood of wood cracking due to the exceeding of the perpendicular tensile strength.

The mechanical properties of wood are intrinsically tied to its cellular structure, notably its tracheids and fibres. Softwood, predominantly used in laminated timber structures in regions like Finland, comprises approximately 90-95% tracheids aligned parallel to the grain, while fibres contribute 6-10% and exhibit a radial orientation (Holmberg *et al.* 1999). This complex composite structure endows wood with anisotropic properties, resulting in directional variations in strength and elasticity (Ramage *et al.* 2017). The anisotropic behaviour causes cracks due to external loading or moisture changes to propagate primarily along grain directions, with cracks in the RL (radial-longitudinal) and RT (radial-tangential) orientations being most prevalent. Such behaviour necessitates a thorough understanding of cracking mechanisms to enhance structural assessments and performance predictions. With three principal directions, there can be six different crack orientations in wood (Figure 1). Due to the anisotropy described above, the cracks that typically occur in wood are in RL or RT directions.

Wood is highly responsive to temperature and relative humidity variatios, due to its hygroscopic properties. Variations in moisture content between the core and surface of wood lead to differential swelling and shrinkage, causing internal stresses that may result in cracking (Figure 2). This phenomenon is particularly relevant for large-scale structures with more pronounced moisture gradients. The growth-ring orientation in the cross-section of the lamellae in glulam must account for such variations to minimise internal stresses and potential cracking due to moisture-induced warping.

In glulam, cracking is not limited to the wood itself but also occurs in adhesive joints, often due to moisture-induced warping of laminations and material quality deviations. As discussed by Mercimek *et al.* (2024), the frequently used finger-joint connections in lamellas can induce cracks to adhesive seams in the finger joint as well as between lamellas. Bond-line delamination in EWP is – defined as cracking along or near the adhesive joint – may pose a significant challenge, as it can compromise the beam's structural integrity. The EN 14080 standard (CEN 2013a) mandate rigorous testing of delamination resistance to ensure adhesive joint strength.

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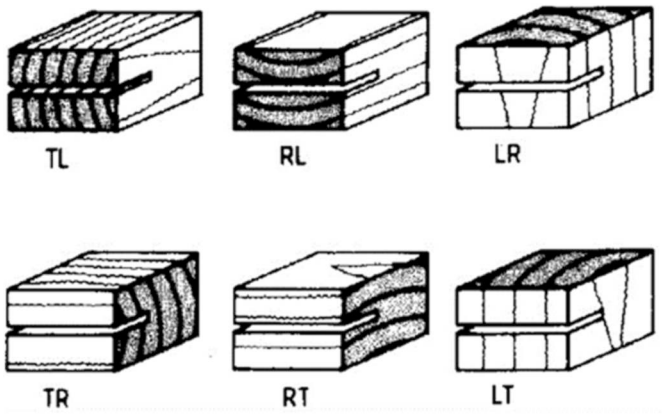

Figure 1. Possible crack orientations in wood.

The present study leveraged insights and expanded the understanding of crack effects on glulam, focusing specifically on the role of crack length. Previous studies by Saracoglu (2011) and Pousette and Ekevad (2012), primarily examined the influence of crack depth and asymmetry on shear capacity. Their experimental results highlighted the disproportionate impact of deep cracks on beam strength due to reduced effective cross-sections, which concentrate shear forces over small areas, increasing the likelihood of structural failure. In contrast, this research emphasises the significance of crack length, demonstrating that longer cracks exacerbate stress distribution challenges and potentially reduce beam durability.

The experimental test results revealed that crack location, depth, and length collectively influence the shear capacity of glued laminated timber beams. As confirmed by Saracoglu (2011), Pousette and Ekevad (2012) and Gaspar *et al.* (2015), asymmetric cracks are particularly detrimental due to uneven stress distribution around the crack tip. It was observed that cracks with depth exceeding 15% of the beam width in the central third of the beam had a profound impact on shear strength, consistent with findings in guidelines issued by the

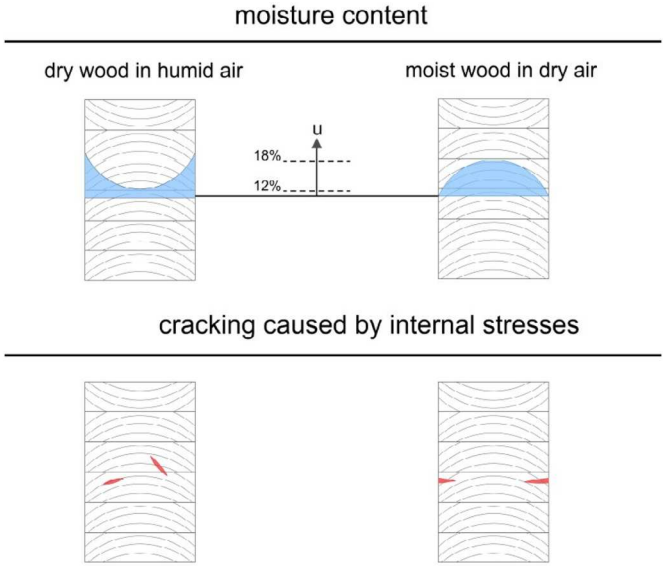

Figure 2. Example of cracking caused by moisture content.

American Engineered Wood Association (APA 2006). However, cracks located away from the beam's central region exhibited less pronounced effects, highlighting the critical role of crack positioning.

Berg *et al.* (2015) extended this understanding by studying side cracks and their relationship to beam height positioning. The side crack occurs on the outer surface of the beam and does not extend to the end of the beam. Their results, which aligned with our observations, indicated that cracks located at mid-height significantly reduce beam strength due to parabolic shear stress distribution across rectangular cross-sections. When multiple cracks were present, their cumulative impact was more severe, underscoring the importance of evaluating crack interactions within the glulam.

This study further corroborates findings by Gaspar *et al.* (2015), which demonstrated that crack depth exceeding 60% of the beam width substantially increased failure risk based on the Hill criterion. Experimental research by Hanegraaf (2018) showed that crack length has a profound influence on glulam beams durability. Additionally, his numerical models showed that beams exhibit behaviour analogous to fully cracked structures when crack length exceeds 35% to 50% of the beam length. Our experimental data supports this assertion, highlighting the necessity of accurate predictive models to better assess crack-induced structural changes in glulam.

The main objective of this research was to examine the impact of crack length and location on the load-bearing capacity of glulam. The main scientific contribution of this study, compared to previous research, lies in its examination of the impact of crack length on the load-bearing capacity of glulam. The findings are highly significant for practical design applications, as they provide more reliability to assessing the criticality of detected cracks in beams and determining the necessary repairs. Given the susceptibility of wood to inherent material variations and external factors such as relative-humidity and temperature variations, this research hypothesised that crack length has a significant impact on the load-bearing capacity and shear strength of glulam. This research aimed to answer key questions, including how variations in crack length affect structural performance and whether these effects align with or deviate from theoretical expectations. By systematically testing over 50 beams with 10 different crack scenarios, this study sought to quantify the influence of crack parameters and clarify on their implications.

2. Materials and methods

Yeh *et al.* (2006) successfully utilised the delamination method in their work, which led to the decision to adopt a similar approach for this research. For these reasons cracks were decided to be implemented as delaminations.

The beams used in the test were manufactured according to the standard EN 386 (CEN 2001), except for the central joint where the delamination was intended to occur. The beams were assembled from two pieces with a cross-section of 115×270 mm, which were produced in accordance with normal production processes on the factory line. A tape corresponding to the desired initial crack dimensions was placed on one of the connecting components to prevent adhesive

Figure 3. The adhesive was applied to the surface of the counterpart. The tape prevents the surfaces from bonding at the intended location.

Figure 4. Counterpart pieces of the beams were being installed in the clamp.

bonding. The adhesive was then applied to one of the connecting components following standard procedures and using a roller, as shown in Figure 3. After the adhesive application, the counterpart components were clamped together, as illustrated in Figure 4. The resulting glulam beam comprised two sections, with an initial crack of tape length and width in the middle of the cross-section. Although the manual method used differed from the conventional production of beams, it is used to fabricate unique structures such as arch beams.

In the previous studies (Franke *et al.* 2016, Hanegraaf 2018), the tests were almost exclusively conducted as three-point loading tests. In all of them, issues were identified with the failure of the reference beam, as it is essential to have the beam fail in shear failure when examining shear strength. Due to the stress state of the beams in three-point loading tests failed through bending, which means shear strength of the reference beams cannot be determined. For this reason, it is nearly impossible to reliably ascertain the actual effect of the crack compared to an intact beam. With the four-point loading method, the resulting stress state differs from that of the three-point loading, such that the reference beam should also fail at the section. This was one reason the four-point loading method was chosen (Figures 5 and 6). In the test loading arrangements, the specific strengths, dimensions, and constraints of the loading frame of the beam were considered. These factors aimed to create an ideal test loading arrangement so that all beams could fail at shear failure.

The test specimens used in the experiments had dimensions of $115 \times 540 \times 2700$ mm and were classified as strength class GL30c. The adhesive used in the beams was a typical melamine-urea-formaldehyde adhesive (MUF adhesive) used in glulam manufacturing. MUF adhesive complies with standard EN 301 (CEN 2013b) adhesive type I. The test loading arrangement is presented in Figure 5. The jacks had a capacity of 250 kN and were controlled based on displacement to obtain more accurate data on the moment of failure of the beams. The crack that led to the beam's failure was marked with a marker so that the deviations affecting the crack could be examined later. A total of 54 beams were tested. In series 1, nine intact specimens were tested, while in the other series, five samples were tested. The series 2 and 3 contained "end crack" delaminations, that initiated from the beam end while in the series 4-10, the delaminations were in the beam length as "side cracks".

Before testing was applied, the beams were inspected for defects and weighed for density calculations. Most defects were found in the middle adhesive joint, where various cracks were located. The length of the cracks was measured, and their depth was assessed using a crack gauge to evaluate their impact on the beam's failure afterwards (Figure 7). Surprisingly, central adhesive joint had many deviations. The cause was likely a work error during gluing or a combined effect of the used materials and the tape. No clear explanation was found for the failure of the adhesive joint, and it requires further investigation.

After the tests, the failure loads, observed deviations, crack locations, and the beam's density were compared. Based on the observations made during the comparison, the impact of the deviations on the beam's failure was assessed. The deviations were categorised into three groups: insignificant cracks, significant cracks, and failed glue joints.

3. Results

3.1. Influence of crack length

The results of the tests were somewhat different from expectations, as the crack length had less impact on the beam's load-carrying capacity than anticipated. The series results are

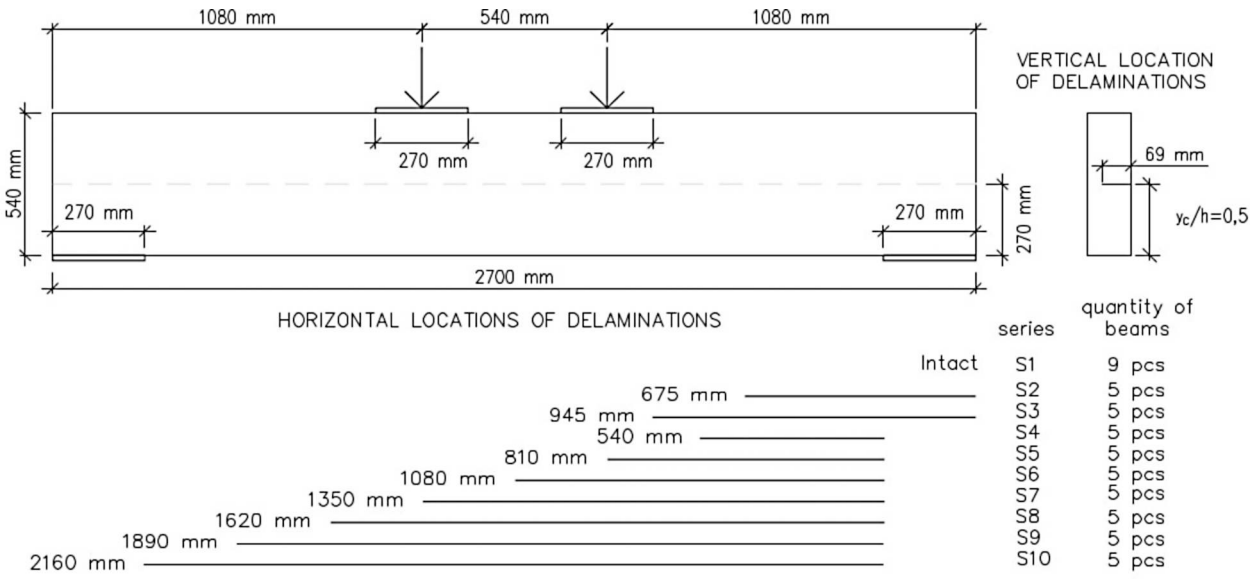

Figure 5. Four-point test setup. Delamination depth, lengths, and locations of the examined series.

presented in a histogram (Figure 8). The calculated shear strength of the intact beam is also plotted on the graph (grey dashed line). As observed, the crack has an apparent effect on the beam's shear strength. Still the load-carrying capacity is significantly greater than what would be expected from the reduced cross-section method that adopts the basic structural analysis but uses the cross-section width value that is reduced by the crack width (Figure 8). However, a clear difference is observed between the intact and delaminated beams, yet the impact of crack growth on the beam's shear strength is surprisingly minimal.

As seen in Figure 8, the critical failure load of series 2 is only 12.8% greater than the failure load of series 10, even though the cracks in series 10 are 1 485 mm longer ($l_c/L = 0.55$ in which l_c is the crack length and L is the beam length). The primary reason for this minor difference is the stress state of the beams. The active shear stress area related to the crack extends to 0.6 lc/L, while only 0.3 lc/L is included within that same active shear stress region.

From series 6 onward in Figure 8, the cracks grow outside the significant shear area. However, series 6–10 do not exhibit the same linear degradation seen in series 2–5. The graph indicates that series 7 and 8 are even more durable. This should be viewed cautiously, as the inherent properties of wood must be considered, given that the sample size for these series is only five pieces. It is essential to note that in series 5-10, the delamination length on a single active shear zone is 0.3*L*. Based on this result, the length of the crack only affects the significant shear stress area. Additionally, the series shows a lower value than series 10, which can be partially attributed to the higher number of manufacturing defects observed in that series beams, as detailed in Table 1.

When examining series 2 and 3, where delamination started from the beam's end and grew to $l_c/L = 0.1$, similar to series 4–5, it appears that increasing the length of the end crack has a greater impact on the beam's durability than a side crack. However, it's worth noting that in series 4, only four beams were loaded due to one failed loading. The results are

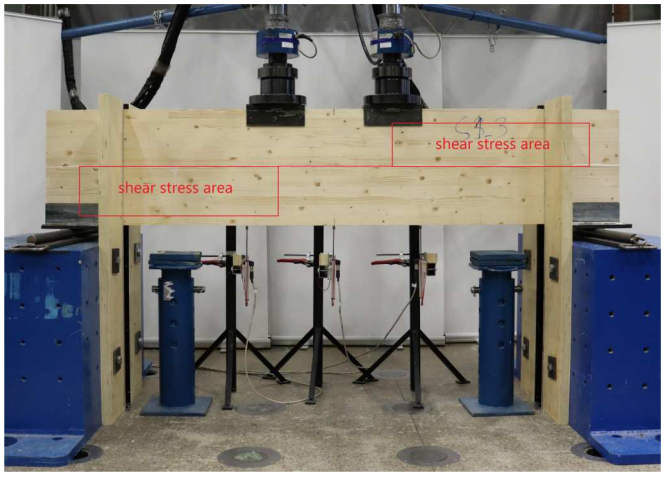

Figure 6. Four-point test arrangement and shear force distribution.

Figure 7. Observations made before the test load. A curve corresponding to the depth of the crack has been drawn on the side of the beam.

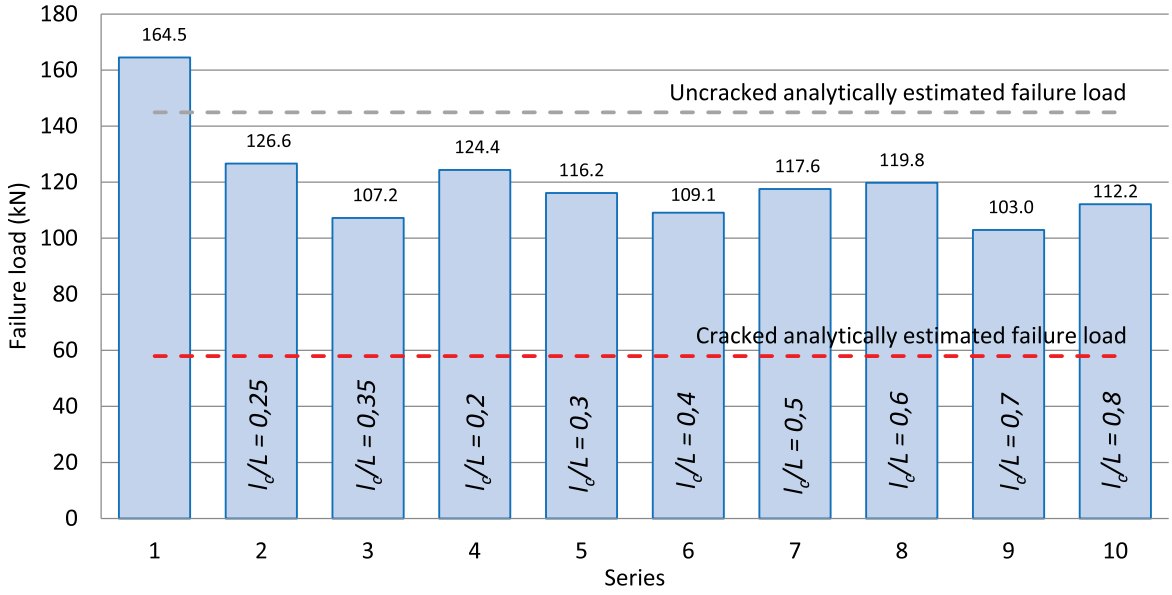

Figure 8. Histograms display average critical loads of the test series and presented lengths are the lengths of the cracks.

Table 1. Classification of the failure modes of the beams and the deviations observed before the test loading.

		Glulam beams								
		1	2	3	4	5	6	7	8	9
Series	S1	A	A	A	A	A	B	B	B	A
	S2	B	B	B	A	B				
	S3	A	B	A	B	B				
	S4	A	A	A	B	C				
	S5	B	B	B	D	B				
	S6	B	B	A	A	B				
	S7	B	A	B	B	B				
	S8	B	B	D	B	B				
	S9	A	D	B	C	D				
	S10	D	B	B	B	A				

Failure type	
	Wood crack
	Delamination
	Other

Observations before test	
A	No deviations
B	Insignificant cracks
C	Significant cracks
D	Failed glue joints

indicative, but for a more precise investigation of the crack type's effects, there should be more test specimens.

3.2. Failure modes

The beams failed during the test loading in three ways: as delamination, wood and other failure. All cracks that progressed into the lamella after the tape were classified as wood failure, while those that advanced purely within the adhesive joint were considered as delaminations, as shown in Figures 9 and 10, respectively.

Beams that failed due to delamination broke at the lowest failure load. The adhesive joint should be more durable than the tensile strength of the wood fibres. Additionally, their force-displacement pattern was linear until failure, while the pattern for wood failures was parabolic (Figures 11 and 12). Based on these observations, the adhesive bond in the delaminated beams was determined to have failed.

The other failure modes mentioned in the table include all other except shear failures. Therefore, these could not be considered in the examination of the results. Some of the beams in the first series failed due to bending caused by deviation, such as a knot or a finger joint. In the third beam of the fourth series, an error occurred in the control of the jack, which affected the test result.

In the lamellas, cracks propagated in the TL, RT, and RL directions. No correlation was observed between the failure pattern of the crack, the progression of the crack or the failure load. Natural cracks at the ends of the lamellas, such as ring cracks, were found not affect the beam's durability (Figure 9). As a side observation, the crack gauge was noted to be a very effective tool for assessing crack depth. Beams with deep cracks measured by the crack gauge also failed under lower failure loads. Furthermore, the failure pattern often corresponded to the crack depth measured by the crack gauge (Figure 9). The beams always failed at the point where the crack started,

Figure 9. Wood failure in the RL – and TL direction. The failure pattern follows the crack observed on the right side.

Figure 10. Failure was classified as delamination.

except for series 10, in which the crack was equidistant from both ends of the beam, resulting in failure occurring at the weaker end.

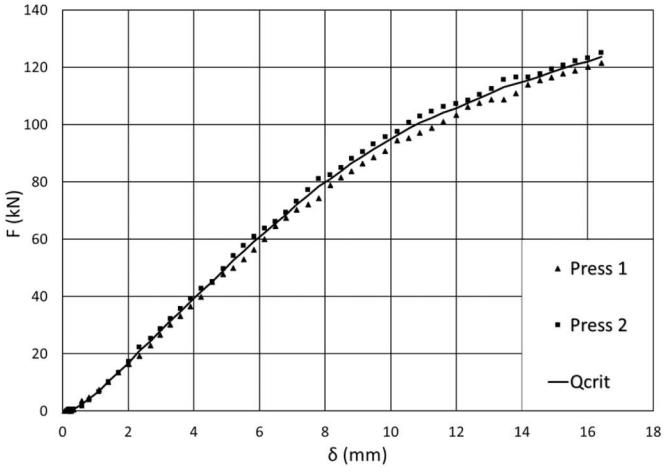

Figure 11. Force-displacement curve of beam S8-2. The beam failed along the interface of the wood fibres.

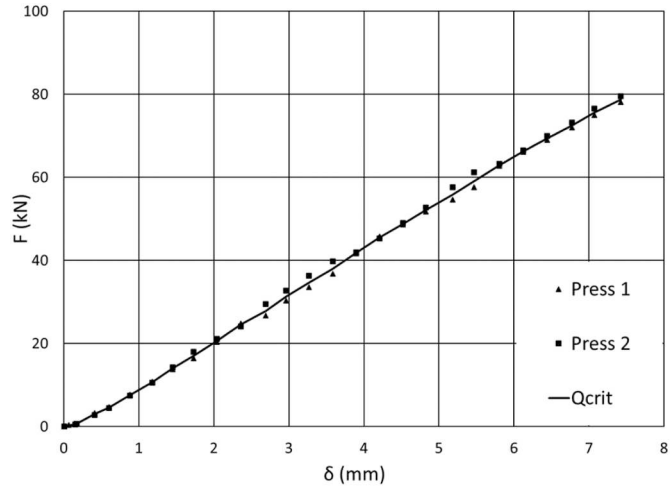

Figure 12. Force-displacement curve of beam S8-3. The failure mode of the beam was delamination.

4. Discussion

4.1. The influence of crack parameters

The length of the crack negatively affects the load-carrying capacity of the beam, as shown in previous studies (Franke *et al.* 2016, Hanegraaf 2018). In those studies, the effect of length was investigated using a three-point loading method, which applies uniform shear stress along the entire length of the beam (Figure 13). In this work, the beams were loaded using a four-point loading method, resulting in three shear stress regions within the beam as shown in Figure 14. A significant observation was how little the growth of the crack affects the beam's durability outside the stress zone. Furthermore, when the crack was situated in all three regions, its length was found to be significant about one of the stress zones. The beams failed at the weaker end when the crack was of equal length in both significant stress regions. Based on the results, it can be concluded that the effects of the crack are significantly influenced by its location in relation to the stresses present in the beam. So, it is essential to consider how large portion of the crack is in the high-stress areas.

The most influential parameter affecting beam's durability is the crack's depth, as demonstrated in numerous previous studies mentioned above. The observations made in this work supported these findings: In this work, the target crack depth was fixed to 60% of the beam cross-section width. However, as depicted in Figure 7, crack depth exhibits some variations. When analysing the failure load results with respect to measured crack depth within each series, certain correlation between the crack depth and failure load could be detected. One noteworthy observation is how conservative the value provided by the reduced cross-section is. All series showed that the beams behaved significantly more durably. This result reinforces previous findings indicating that the beam is clearly stronger than the reduced cross-section method suggests.

Additionally, it is essential to highlight the location of the crack, which is not considered in the reduced cross-section method. In all test specimens, the delamination was in the

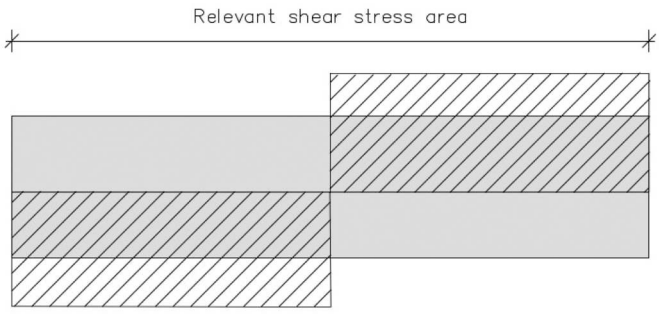

Figure 13. Impact area where the increase in crack length is significant when the beam is three-point loaded.

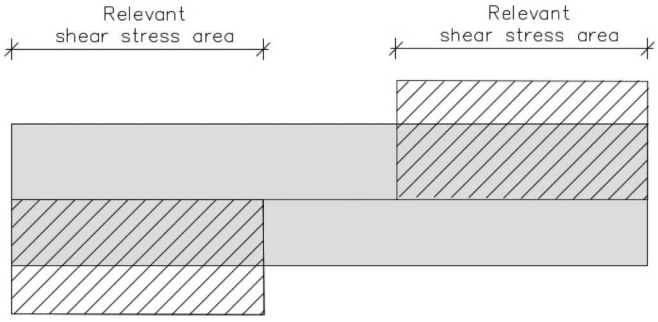

Figure 14. Impact areas where the increase in crack length is significant when the beam is four-point loaded.

middle of the cross-section, where shear stresses were at their highest. Therefore, it had the greatest possible negative impact on the beam's shear strength. If the crack is located further from this neutral axis, its effect on the beam's shear strength diminishes. In such cases, the method's estimated strength further underestimates the beam's actual durability.

Figure 15 illustrates the key factors that should be considered when evaluating the durability of the cracked beam. The aspects presented are based on the observations from this research and the findings from the literature review of other researchers.

4.2. Crack propagation and failure modes

In this study, the crack that led to delamination and subsequent failure almost invariably extended into the wood, except for the beams that failed at the adhesive joint. The adhesive joints proved to be more durable than the wood itself, as required by the standards. Beams that failed in this manner exhibited significantly less variability in their failure loads compared to those that failed purely due to delamination. Furthermore, the behaviour of the delaminated beams during loading

Table 2. The key findings of this study.

The effect of crack parameters on the load-bearing capacity of glulam beam	
Results of this study	Growth of crack length negatively affects the beam's load-bearing capacity in the shear stress area.
Results of other studies	The depth and location of the crack have been found to have a more significant effect on the beam's load-bearing capacity. There is no clear understanding of the effect of crack length.
Theory	The assessment of the load-bearing capacity of a cracked beam is based on the effective width and the parabolic shear stress distribution.
Conclusion	In the assessment of load-bearing capacity, all parameters of the crack should be taken into account.
The effect of crack type on the load-bearing capacity of glulam beam	
Results of this study	Delamination that led to the failure proceeded from the adhesive joint to the lamella. The failed adhesive bond led to failure under significantly lower load.
Results of other studies	Crack that occurs in the wood leads to a similar failure behaviour. Effects of cracks have been studied using saw-cut cracks
Theory	Glulam should initially crack at the lamella when wood's perpendicular tensile strength is exceeded, as the adhesive joint is expected to be more durable.
Conclusion	The load-bearing capacity of the cracked glulam should be assessed based on the strength properties of the wood, regardless of the type of crack. Additionally, the risk of crack growth should be taken into account based on the causes.

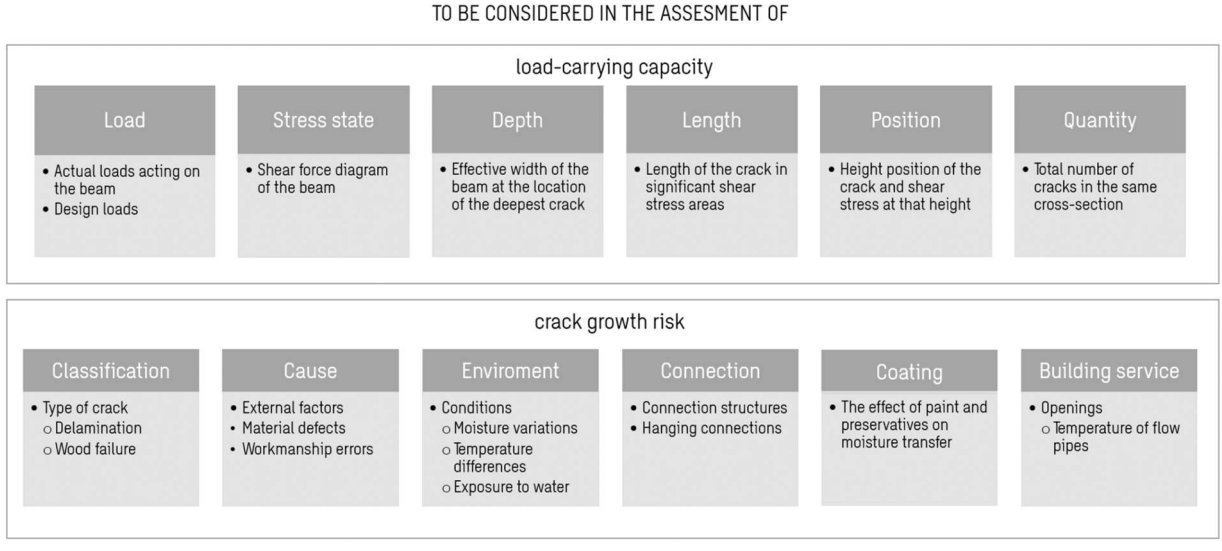

Figure 15. Factors to consider when assessing the durability of a cracked beam and the significance of the crack.

clearly differed from the others; they failed at noticeably lower loads than the beams that failed in the usual manner.

This is a critically important observation because if the cause of delamination is the inadequacy of the adhesive joint, the beam may fail at a significantly lower load than designed. Its durability is impossible to assess analytically if it results from material or workmanship errors. It is noteworthy that the deviations observed in this experimental study occurred only in manually made adhesive joints, while no deviations were found in machine-made adhesive joints. Variations in moisture often lead to minor cracks near the adhesive joint, making the investigation of a faulty adhesive joint very challenging. For this reason, when examining delaminated beams, it is important to consider all adhesive joints and contact the manufacturer if necessary, regarding previous observations. Table 2 compiles the key findings of this study. Additionally, it presents the findings from previous research and the theoretical approach.

4.3. Limitations of the tests

This study has several limitations that should be considered when interpreting its findings. First, it focused exclusively on delaminations located in the middle of the cross-section of glulam, which may not fully represent the diverse crack types and locations encountered in real-world applications. Additionally, this research primarily investigated the effect of crack length, potentially overlooking other critical parameters such as crack orientation, depth, or interaction with environmental factors like moisture and temperature fluctuations, which are known to influence wood behaviour. The controlled testing environment, while valuable for isolating specific variables, may not fully replicate the complex and variable conditions under which timber beams are used in practice. Furthermore, this study's findings are based on a limited sample size of 50 beams and 10 crack scenarios, which, while extensive, may not capture the full variability of engineered wood products. These limitations suggest that further research is needed to explore a broader range of crack parameters and environmental conditions to ensure the findings' applicability across diverse structural contexts.

Future studies should aim to expand upon this research by investigating a wider range of crack parameters, including depth, orientation, and interaction effects, to develop a more comprehensive understanding of how these factors influence the structural performance of glulam. Research should also consider the impact of environmental variables such as varying moisture levels, temperature fluctuations, and prolonged exposure to load, which closely mimic real-world conditions.

5. Conclusions

The primary objective of this study was to explore the influence of crack length and location on the load-bearing capacity of glulam by testing over 50 specimens across 10 different crack scenarios. Crack depth is the most critical factor affecting the shear strength of glulam beams, as it directly correlates with the concentration of shear stresses. While crack length influences shear strength in high-stress areas, its overall impact is less significant than expected in the light of the simplified structural analysis method, highlighting the importance of assessing cracks about the stress state rather than solely based on their dimensions. Additionally, crack location plays a more significant role in structural reliability than crack length, emphasising the need for location-based evaluations in design considerations. The experimental delamination method effectively replicated real-world failure patterns, confirming that adhesive joints consistently outperform wood in strength, making this method preferable to mechanically induced cracks for future research. From a practical perspective, quality control measures should minimise cracks during manufacturing and ensure early detection and repair to maintain structural integrity. Design guidelines should accommodate the presence of cracks while emphasising manufacturing techniques that reduce delamination risk. Regular inspections and maintenance should be implemented to identify and mitigate crack-related issues before they affect beam performance. Finally, industry standards should integrate these findings to enhance engineered wood products' safe and efficient use in demanding structural applications.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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