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Review

Structural Assessment Techniques for In-Service Crossarms in Power Distribution Networks

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Abstract: Crossarms are widely used in power distribution and telecommunication sectors to support overhead cables. These structures are horizontally attached to the top of vertically erected utility poles and are essential elements in connecting overhead cables to the poles. Timber is the dominantly used material type for crossarms in the existing distribution networks. Nevertheless, there are alternative crossarms made from steel, composites, polymers, and even from concrete. This paper reviews the studies on the condition assessment of timber crossarms considering the aspects of decay identification and flexural strength assessment. The limitations and shortcomings of the conventional inspection techniques for crossarms are presented. Then, the studies on the developments of non-destructive test methods to address these issues are reviewed. Further, the results from the experimental work conducted to assess the structural capacity of in-service crossarms are presented and analysed. In addition, the possible future advancements of alternative crossarm types are also discussed, considering the mechanical strength, durability performance, and sustainability aspects. This paper aims to highlight the advantages and disadvantages of different condition assessment techniques for crossarms, indicating the importance of an integrated approach combining both the conventional and non-destructive testing techniques.

Keywords: condition assessment; non-destructive testing; decay; failure analysis; sustainability; durability performance

Citation: Rajeev, P.; Bandara, S.; Gad, E.; Shan, J. Structural Assessment Techniques for In-Service Crossarms in Power Distribution Networks. *Infrastructures* **2022**, *7*, 94. https://doi.org/10.3390/infrastructures7070094

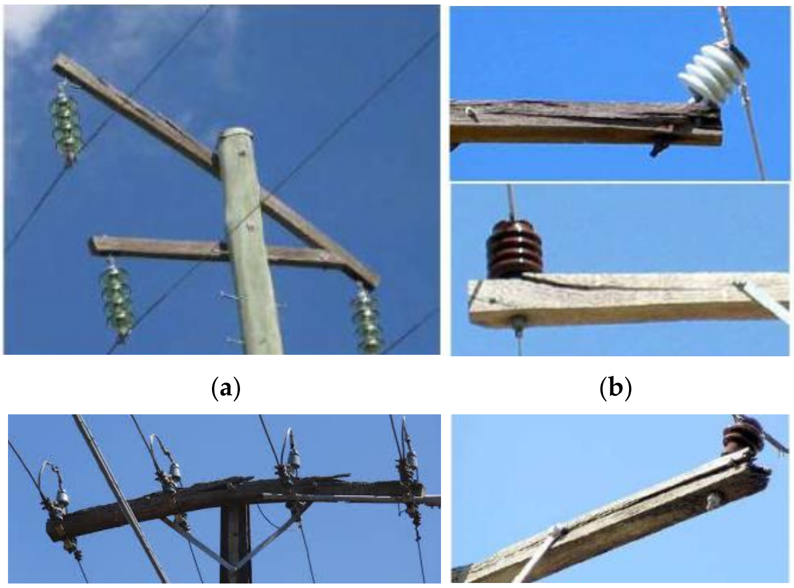
Academic Editor: GM Shafiullah

Received: 15 June 2022
Accepted: 17 July 2022
Published: 19 July 2022

1. Introduction

Timber elements such as utility poles and crossarms are extensively used in power distribution networks in Australia and around the world. Pandey et al. [1] reported that there are more than 40,000 timber H frames supporting around 7000 km of 115 kV transmission lines alone in the province of Ontario, Canada. In the United States, there is an estimated amount of over 100 million timber poles supporting electrical transmission and distribution systems. All these poles are connected to one or more crossarms [2]. In the North American countries, Douglas fir is the widely used timber species for crossarms [3]. In the Australian context, there is an estimated amount in excess of 5 million timber poles privately owned by the power distribution companies [4]. About 40 to 50 million dollars are annually spent for the maintenance and management of these assets by the Australian power industry [5].

Timber is selected for crossarms over the alternative materials (e.g., steel, composites, and concrete) due a number of relative advantages, of which higher strength-to-weight ratio, long service life, excellent insulation properties, economical, and renewable aspects are the main factors. Nevertheless, as a biodegradable material, deterioration of timber is inevitable due to the sources of weathering, decay, and termite attack [6]. The cyclic nature of wet and dry conditions, exposure to high and low temperatures, and direct exposure to sunlight causes weathering, which results in the degradation of wood surface [7]. Wood decay is also caused by fungal attack, which is a result of the interaction between organisms that utilise timber as a source of food for their growth [8]. Termite attack is not very common for timber crossarms given the location of these structures, typically about 8 to 15 m from the ground level. The deterioration processes can lead to reduction of the cross-sectional area of crossarms, change of timber material properties, splitting, and wood cell erosion. Figure 1 illustrates the deteriorated and failed timber crossarms subjected to the aforementioned causes. Flexure-induced splitting was observed in the majority of the crossarms. It is evident that most of the crossarms have failed or initiated the failure close to the location of end bots, which are supporting the insulators. Additionally, some failures can be observed at the vicinity of king bolt located at the centre of a crossarm, which is connecting the crossarm to the pole. The primary reason for this is the retention of moisture in bolt holes and the reduction in effective cross-sectional area of the crossarm due to the presence of the opening for the bolt to run through.



(**a**) (**b**)

(**c**) (**d**)

Figure 1. Deteriorated and failed timber crossarms due to decay and aeolian vibrations; (**a**) failed crossarm losing an insulator; (**b**) splitting at the end bolt locations; (**c**) badly split crossarm along the length; (**d**) losing sound wood at the end of the crossarm.

Except for the decay in crossarms, loosely connected king bolts and end bolts lead to enlargement of the bolt holes due to aeolian vibration. Alternating lift and drag forces induced by wind generate vibrations of overhead cables and these subsequently affect the crossarm connections. Improper bolted connections of the crossarms have a substantial effect of these vibrations initiating bolt hole enlargement. Continuation of the vibrations results in rapid progression of the bolt hole enlargement, which supports the retention of moisture and, thus, accelerated decay rates. Further, additional structural connections to crossarms exceeding the design specifications can be commonly observed in power distribution networks. Excessive load resulting from additional connections exceeding the design load can increase the probability of sudden crossarm failure without prior indications. The effects of these causes on timber crossarms are amplified, as wood is a natural material consisting of imperfections such as knots, splits, and slope of grain.

An accurate estimation of the remaining service life of crossarms is crucial for timely replacements that can avoid failures. Therefore, different condition assessment techniques are implemented in the field, considering the aspects of simplicity (ease of operation), accuracy, reliability, and safety of the operator. The conventional crossarm inspection techniques include visual inspection and sounding. However, given the subjective nature of these assessment techniques, more attention is paid towards the advancements in non-destructive testing (NDT) methods, which can eliminate the subjectivity and provide accurate results [9]. More focus on NDT techniques for timber structures are on stress wave propagation, ultrasonic pulse velocity, vibration-based techniques, and tomography techniques (e.g., [10–12]). The stress wave propagation technique is based on generation and propagation of either a longitudinal or transverse stress wave within the structure. Reflection patterns of the wave behaviour can be analysed to identify potential defects [13]. In the ultrasonic pulse velocity technique, the time-of-flight method is utilised to determine the wave propagating speed, and this speed is generally used to comment on the condition of the tested structure [14]. Vibration measurements are obtained in vibration-based techniques to correlate the strength with derived vibration properties and then to access the structural integrity. Tomography techniques provide local condition assessment by scanning the structure at selected locations and by evaluating the density [15]. In addition to NDT techniques, flexural behaviour of crossarms is also investigated via laboratory experiments to understand the performance of intact and deteriorated crossarms belonging to different species.

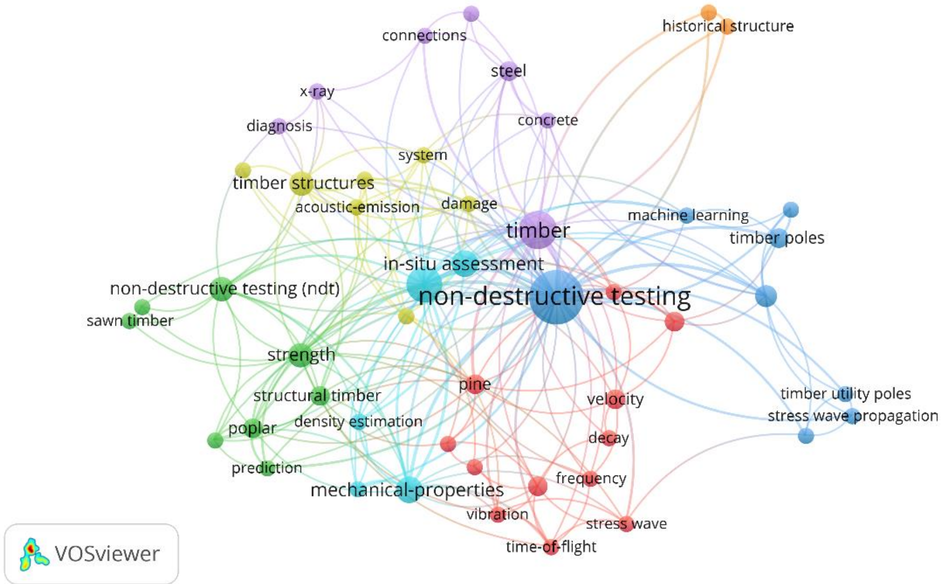
Given the presence of a wide variety of condition assessment techniques for crossarms, such as conventional inspection techniques, flexural strength assessment tests, and non-destructive test methods, it is challenging to select the most suitable condition assessment technique considering the aspects of reliability, accuracy, simplicity of operation, and cost. Therefore, this paper reviews the studies on the condition assessment of timber crossarms, considering the aspects of decay identification, flexural strength assessment of crossarms, and non-destructive test methods, highlighting the advantages and disadvantages of each technique. Moreover, the results from the experimental work conducted to assess the structural capacity of in-service crossarms are presented and analysed. In addition, the possible future advancements of alternative crossarm types are also discussed, considering the mechanical strength, durability performance, and sustainability aspects. The overall aim of this study is to facilitate the power network management by providing a thorough understanding of the structural health assessment techniques of crossarms.

2. Methodology for Literature Review

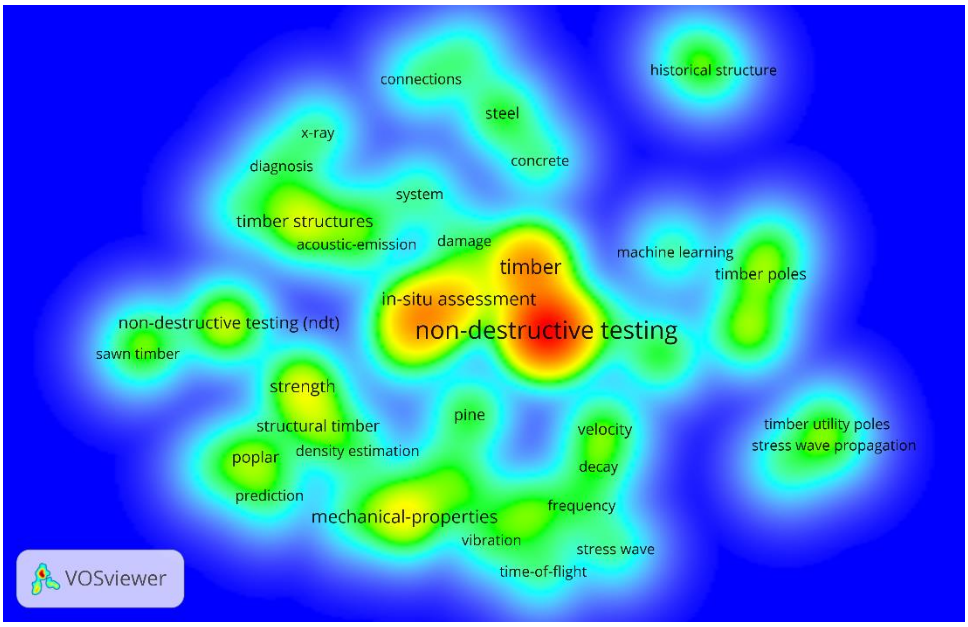
A comprehensive literature review was conducted on the structural assessment techniques of timber crossarms used in power distribution networks. Non-destructive testing of timber crossarms, destructive testing of timber crossarms, structural deterioration, strength characteristics, and structural capacity were investigated through journal articles. The Web of Science (WoS) database was used to perform a bibliometric analysis, and the search string used in the analysis is given below in Table 1. It should be noted that the review is performed to draw conclusions for the existing methods for non-destructive testing of timber crossarms. VOSviewer software was used to compare and observe various trends and occurrences of the keywords related to the above-mentioned literature. A total of 230 journal articles from 1969–2022 were selected from WoS and a network visualization diagram and a density visualization diagram for co-occurrences were created using VOSviewer, as shown in Figure 2. A network or density visualization diagram includes different labels, and the size of the label (circle) represents the weight of the item: the bigger the label, the larger the number of co-occurrences the item holds. The colour of an item in the network diagram represents different clusters. The analysis here includes 49 items and 7 different clusters with 219 links. According to the network visualization and the density visualization shown below, major keywords or items appearing in the context are non-destructive testing, in situ assessment, mechanical properties, timber, and wood, which indicates that those are the most researched keywords. Various other keywords are linked to those major keywords.

Table 1. Search string used for the bibliometric analysis.

Year	Sources	Search String
1969–2021	Web of Science (All Fields)	AND timber, AND "non-destructive testing" OR "destructive testing", OR "timber cross arms", OR deterioration, OR "composite cross arms", OR weathering, OR "visual inspection"



(**a**)



(**b**)

Figure 2. Co-occurrences of keywords. (**a**) Network visualization diagram. (**b**) Density visualization diagram.

3. Conventional Crossarm Inspection Techniques

The conventional crossarm inspection techniques are visual inspection and sounding technique. These methods are carried out by experienced inspectors by reaching the top of a utility pole to access the crossarm. The visual inspection technique can identify the presence of external defects within a crossarm, such as decay pockets, checking, splitting, and wood cell erosion. The main limitation of the visual inspection is the inability of identifying potential internal defects. The sounding is carried out by striking the crossarm at different locations using a handheld hammer. The generated sound and the rebounding effect of the hammer are observed to comment on the condition of the crossarm. A degraded crossarm with the presence of defects produces a dull sound and a relatively weak, or no, rebound. From the observations of the visual inspection and sounding, the inspectors provide ratings for crossarms. These ratings are recorded in the field itself and post-processing of results are not required. The conventional inspections operations are carried out typically around every five years, depending on the policies of the network owners. However, the frequency of inspection cycles can vary in bush-fire-prone areas and in regions with aggressive environments, leading to accelerated decay rates.

Relying on the assessment ratings provided by the inspectors, utility network managers decide on the replacement of crossarms. Results obtained from the conventional inspection techniques are subjective and, thus, the reliability of the results are in question. To carry out these inspections, crossarms should be accessed that are located about 8 to 15 m from the ground level. The presence of overhead cables brings safety concerns for the inspectors in reaching a utility pole top. Moreover, the overhead cables are running for thousands of kilometres in a power distribution network and individual pole climbing for the condition assessment of crossarms may be time-consuming and not efficient. These are the main limitations and drawbacks of the conventional inspection techniques. To address the difficulty in reaching the crossarms, some visual inspections are carried out by observing the condition of crossarms from the ground, as illustrated in Figure 3. However, the accuracy of the obtained results is in question, given the limitation of the observations that can be made from the ground (e.g., cannot make any sort of observations about the top surface of the crossarms).

Figure 3. Visual inspection technique carried out from ground [16].

4. Decay of Timber Crossarms and Decay Identification

The decay is caused by fungal attack, and different timber species possess different inherent resistance levels for decay. In Australia, three types of fungus are identified, namely, brown rot, white rot, and soft rot. This categorisation is based on the chemical components of wood which they are attacking and the colour of infested wood [17]. Wang et al. [18] investigated the decay rates and identified that there is a difference in the decay rates even across a cross-section of a timber log. For untreated timber, sapwood indicated the highest decay rate in comparison with inner and outer heartwood. When sapwood was treated, it had a lower decay rate compared to heartwood. Therefore, the treatment process has substantial effects on the decay of crossarms. For the preservative treatment of timber, copper chromium arsenate (CCA), alkali copper quaternary (ACQ), and creosote can be used.

Retention of moisture on the bolt holes and the top surface of crossarms is identified as a major cause for increased decay rates. Khalid et al. [19] explored the capability of decay detection in wooden crossarms by implementing the microwave reflection method. The crossarms were categorised into three distinct groups, such as severe decay, incipient decay, and sound wood. This categorisation was based on the amount of moisture that can be absorbed by wood and the density of wood based on different decay stages. Results indicated that the proposed method was able to measure the defective area up to 2 cm from the surface of wood. Further, Khalid et al. [20] investigated the applicability of ultrasonic techniques to find a suitable method of measurement to determine the decay under the connecting metal blocks. For this ultrasonic pulse velocity method, the time-of-flight method was employed in the analysis to assess the condition of the crossarm. With the increase of the degree of defect, ultrasonic wave traveling times were observed to be increasing. Thus, the ultrasonic wave transit time was an indirect measurement providing the presence and degree of decay in wooden crossarms.

The remaining strength of a crossarm is directly related to the degree of surface decay. Ho et al. [21] developed a statistical model which correlates the amount of surface deterioration to the remaining strength of rectangular Douglas fir crossarms. An image processing technique was employed to accurately quantify the amount of deterioration. The image processing technique could overcome the subjectivity involved in the conventional visual inspection technique. It was identified that the decay in a high-stress zone has a prominent influence on the loss of strength compared to the decay in a low-stress zone. The high-stress zone of a crossarm was chosen as 1 ft from each side of the pole support. In addition, it was noticed that the presence of natural imperfections such as knots and slope of grain affected the remaining strength of a crossarm.

5. Flexural Strength of In-Service Crossarms

Timber, as a natural material, inherits imperfections and growth defects. Some of these are the slope of grain and presence of knots, splits, and checks. Standards specify the requirements and guidelines to be considered when selecting suitable timber for crossarms (e.g., [22–24]). These standards specify limits for the allowable knot size, slope of grain, checking, splitting, and presence of other defects. Researchers have paid attention to investigating the flexural strength of crossarms by conducting bending tests. Different species of wood, different crossarm geometries, effect of strengthening techniques, and effect of decay and knots are explored in terms of the bending capacity. Three-point and four-point bending tests are conducted for full-scale crossarms, or sometimes only for the critical regions of crossarms, to determine the bending strength parameters, such as modulus of rupture (MOR) and modulus of elasticity (MOE). A summary of the studies on flexural strength assessment of timber crossarms is presented in Table 2.

Table 2. Studies that examined the flexural strength of timber crossarms.

Study	Crossarm Dimensions, Species, Number of Specimens Tested and Remarks	Results and Remarks (Mean Values of MOR, MOE)
[3]	89–114 mm and 95–120 mm, Douglas fir. 89–114 mm and 95–120 mm, Southern Pine. 35 specimens of 2.4 m span.	Southern Pine: MOR 75.9 MPa, MOE 13.8 GPa. Douglas fir: MOR 63 MPa, MOE 15 GPa. Southern Pine: MOR 75.9 MPa, MOE 13.8 GPa.
[25]	95–120 mm, 2.5 m span. 5 species were tested with 60 specimens per species.	Piquia: MOR 69.9 MPa, MOE 10,580 MPa. Tauari Vermelho: MOR 59.2 MPa, MOE 7650 MPa.
[26]	Circular crossarm specimens of average diameters of 18.5, 22.2, 25.2, and 27 cm, 9.1 m span. Western Red Cedar: 7 specimens. Northern White Cedar:11 specimens. Jack Pine: 26 specimens.	Western Red Cedar: average strength 32.8 MPa. Northern White Cedar: average strength 28.9 MPa. Jack Pine: average strength 33.3 MPa. Red Pine: average strength 40.5 MPa.

Table 2. *Cont.*

Study	Crossarm Dimensions, Species, Number of Specimens Tested and Remarks	Results and Remarks (Mean Values of MOR, MOE)
[27]	89–114 mm, 2.44 m span. Southern Pine: 60 specimens. Douglas fir: 60 specimens. Compared the flexural strength parameters with previous findings of [3].	Southern Pine: MOR 70.5 MPa, MOE 13.4 GPa. Douglas fir: MOR 59.8 MPa, MOE 13 GPa. Comparison of strength parameters over a 20-year interval showed that these parameters have reduced due to silvicultural processes and other changes.
[28]	93.8–118.8 mm, Douglas fir, 250 specimens, span 2.4 m. Tested both rejected (according to specifications) and intact crossarms. 200 rejected specimens and 50 accepted specimens.	Accepted specimens: MOR 76 MPa, MOE 7537 MPa. Rejected specimens: MOR 65 MPa, MOE 6715 MPa. Most of the rejected specimens (due to presence of knots) illustrated higher MOR than the requirement in American standard specification.
[29]	Tests were carried out to evaluate the strength enhancement via glass-fibre-reinforced polymer wrap (GFRP). Circular crossarm specimens with diameter 229–286 mm, 3.2 m span, 3 reference specimens, 3 specimens strengthened with GFRP (wrap thickness 0.6 m and 1.2 m), and crack-filled surface preparation.	Reference specimens: MOR 28 MPa. Strengthened specimens: MOR 39.9 MPa. GFRP wrapping had substantial improvements in the flexural strength.
[30]	Tests were carried out to compare the bending strength of laminated specimens with solid sawn specimens. 89–114 mm and 95–120 mm, 3 different spans of 2.1, 2.4, and 3 m, Douglas fir. 10 specimens—solid sawn timber. 10 specimens—vertically laminated. 27 specimens—horizontally laminated.	Solid sawn specimens: MOR 60.1 MPa. Vertically laminated specimens: MOR 50.6 MPa. Horizontally laminated specimens: MOR 46.9 MPa. 5 horizontally laminated specimens and 1 vertically laminated specimen failed at finger joint location. Laminated crossarms can reach the strength specifications for solid sawn crossarms under proper quality control.

Some of the previous studies have neglected the way in which the crossarm is connected to the utility pole and the connection of the crossarm to the overhead cables. Figure 4 illustrates a single crossarm and double crossarm assembly presented in [31]. A 20 mm bolt, typically called the king bolt, connects the crossarm to the utility pole and a gain block is placed in between to have a strong connection. This connection detail needs to be replicated in the bending test setup. Schematic representation of the three-point bending setup is illustrated in Figure 5a and the actual test setup is shown in Figure 5b. Vertical supports are provided at around 100 mm from the two ends of the crossarm specimens. Authors carried out three-point bending tests for 110 decommissioned timber crossarms collected around various parts of Victoria, Australia. These specimens were from three different power distribution networks. A king bolt was placed at the middle and a displacement-controlled load was applied, according to the Australian standard specifications. Breadth of the rectangular specimens ranged from 85 to 125 mm and the height range was 70 to 155 mm. Test spans varied from 1.7 to 2.5 m, depending on the crossarm geometry, and the bolt sizes were 20, 25, and 30 mm. Tested specimens were from different species belonging to both softwood and hardwood.

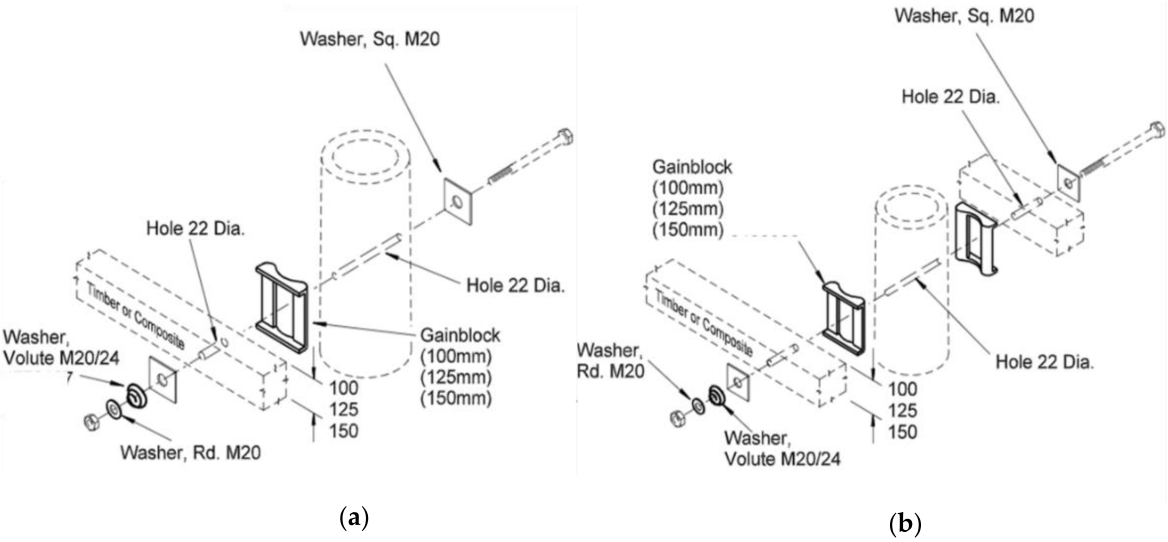


Figure 4. Predrilled crossarm assembly: (**a**) single crossarm; (**b**) double crossarm [31].

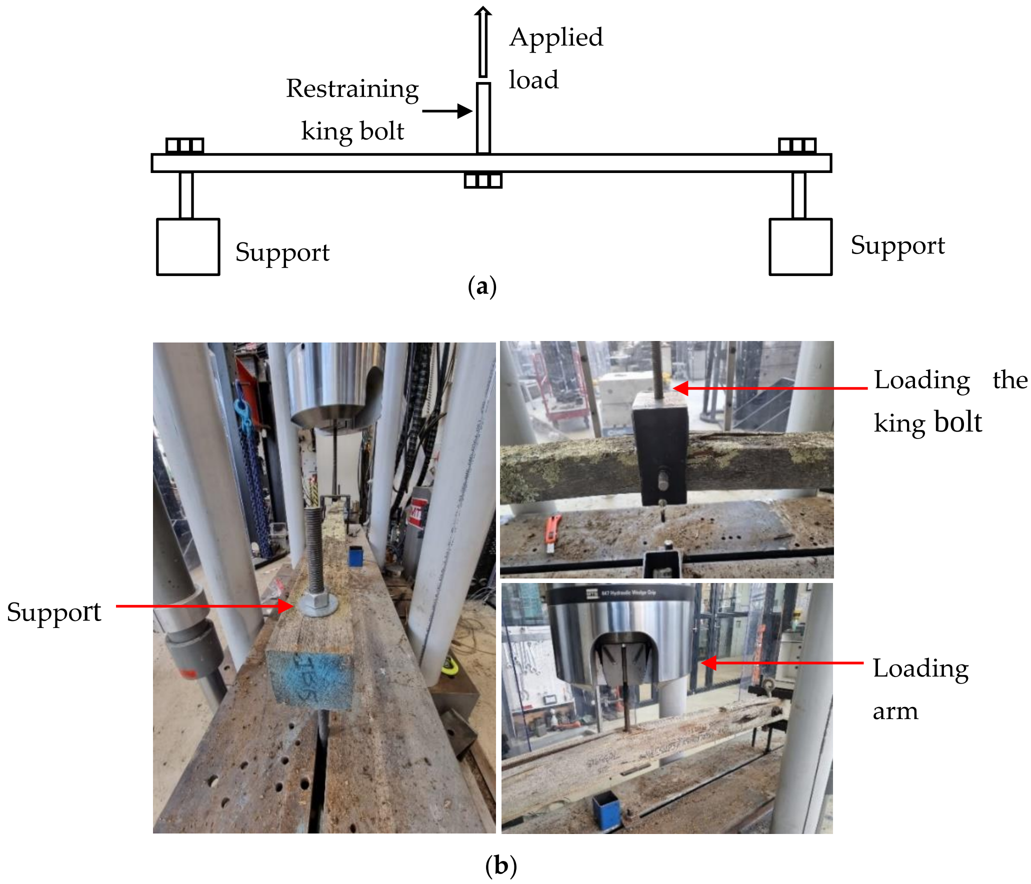


Figure 5. Three-point bending test setup: (**a**) schematic representation; (**b**) actual test setup.

Figure 6a illustrates the cumulative frequency distribution of the MOR for the tested crossarms. The MOR indicates the failure flexural strength of tested specimens. The failure load was recorded from the experiments for each specimen to calculate the failure moment. The section moduli of crossarms were calculated using the measured breadth and height. Then, the simple bending theory was used in calculating the MOR with the use of failure moment and the section modulus. From the visual examination before the testing, crossarms were observed having light, moderate, and severe degradations. Therefore, a significant variation of the MOR can be observed, as evidenced in Figure 6a. When a crossarm is subjected to deterioration, the material properties, such as density and MOE, can degrade, leading to reduced fibre strength. In addition, deterioration can result in loss of sound wood, reducing the effective section modulus. This depletion is substantial if the loss of sound wood is from the exterior of the crossarm rather than from the interior, since loss of material at the perimeter of the cross-section will have the highest reduction in the section modulus. The highest and lowest MOR were 123 and 2.1 MPa, respectively. The average MOR for the tested 110 crossarms was 52.5 MPa. Except for the degree of deterioration of a crossarm, the species of wood belonging to softwood or hardwood and its strength grading directly affected the bending strength indicators. Bending tests were carried out using condemned crossarms from service and finding a relatively large number of crossarms from the same timber species is practically challenging. Thus, the influence of timber species on the calculated MOR cannot be avoided when interpreting the results. Figure 6a indicates that ~50% of the tested poles had MOR values lower than 50 MPa. Figure 6b denotes that about 35 crossarms showed MOR above 60 MPa, which corresponds to light deterioration. These crossarms with a MOR above 60 MPa can still be used in the field, although they have been condemned. This reflects the inaccuracy of the current practices in the condition assessment: specifically, misdiagnosing the defects. Critical region of the crossarms was found to be around the king bolt where the highest stresses are present. The calculated MOR values for the tested specimens can be used to benchmark the health ratings of inspectors to improve the visual examination rating system. Visual examinations were carried out by inspectors before condemning the tested crossarms. Thus, each tested crossarm possesses visual examination results and health ratings based on the examination. Once bending tests are carried out, flexural strength of each crossarm is determined, and subsequently, the health rating of inspectors can be benchmarked. If a particular crossarm with a good health rating from visual inspection is providing a lower MOR from bending tests, it indicates that the visual examination has overlooked defects. When it is the other way around, it indicates that the visual examination has misdiagnosed defects.

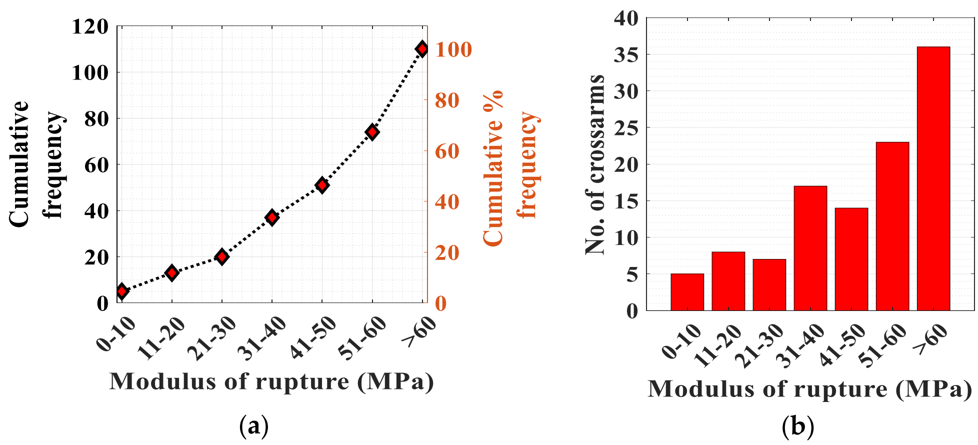


Figure 6. (**a**) Variation of the modulus of rupture—110 specimens; (**b**) groupings of the modulus of rupture.

6. Non-Destructive Testing (NDT) Techniques for Crossarms

The degree of subjectivity involved in the conventional inspection techniques can be eliminated by adopting NDT techniques to obtain accurate and reliable results. The typical approach in most of the NDT methods is to correlate a non-destructive measurement to the strength parameters of crossarms. Miller [32] proposed the use of vibration measurements in crossarms to estimate the strength parameters. The vibration properties are greatly influenced by mass and stiffness. The degradation processes changes the stiffness of a crossarm, leading to changes in the vibration properties. Vibration measurements were undertaken in 50 crossarms which were later subjected to static bending tests. Then, the vibrational properties were correlated with the strength in obtaining relationships which can be later used to estimate the strength of crossarms by conducting vibration tests. Nevertheless, a major limitation of this method is the effect of cables and other attachments for the vibration measurements. These effects cannot be eliminated or at least isolated in field vibration measurements of in-service crossarms. Stack et al. [33] used the broadband acoustical energy generated by a helicopter's rotor to excite a crossarm and measured the vibrations utilizing a helicopter-based laser vibrometer. For the post-processing, artificial neural network models were employed to estimate crossarm breaking strength using vibration spectra. This is a non-destructive, non-contact, and reliable method for condition assessment of crossarms. However, the economic aspects can limit the field application of this technique.

Weathering of crossarms result in roughening the surface. This leads to increased retention and absorption of moisture. Khalid et al. [34] investigated the capability of relating the quality of a crossarm to the amount of moisture content within a crossarm. Dielectric measurements were taken from sound wood, incipient decay, and severely decayed crossarms. These measurements were correlated with the moisture content to conclude about the condition of crossarms. Barras [35] explored the gamma ray propagation technique to access the structural integrity of crossarms. A hammer device and a detector system were developed to calculate discriminants of crossarm strength by post-processing the gamma ray measurements. The wave propagation speed, density of the crossarm, and hardness of the wood at the hammer blow location were determined from the measurements. These parameters were then used to estimate crossarm strength.

Improved Inspection Using Aerial Photographs

Even for the NDT techniques, reaching the crossarm is essential to take the required measurements. To address this issue, aerial photogrammetry techniques can be implemented, where photographs of the crossarms are taken by unmanned aerial vehicles (UAVs). These high-resolution photographs can be analysed to decide on the structural integrity to carry out required asset replacements. Pandey et al. [1] developed a visual condition rating system to grade the high-resolution aerial photographs of crossarms depending on the degree of deterioration. The developed condition rating system was validated by conducting laboratory bending tests on full-scale crossarm specimens. It was concluded that the aerial inspection complemented by the developed visual rating system provides a fast, simple, economical, and reliable method for prioritising the replacement of in-service crossarms. Spatial information captured from UAVs has a great potential in automatic surveillance of power distribution infrastructure, especially for automatic power line detection. A lot of researchers have focused on UAV-based improved inspection techniques and observed that the time taken for inspection can be greatly reduced and the efficiency can be improved tremendously (e.g., [36–40]). These improved inspection methods have been incorporated with background noise removal techniques and fully automatic inspection systems without requiring manual intervention on the ground station or control centre. Silva et al. [41] presented an adaptive digital image processing algorithm to improve the identification and classification process of wood crossarms using automated image inspection. The proposed adaptive algorithm was based on the adaptive digitized straight-line segments that sum up the capability of dynamic change of image segmentation processes such as binarization and contour extraction. Test results indicated that the proposed technique significantly improved the image segmentation process.

UAV-based monitoring and inspection techniques are often complemented by deep learning for data analysis (e.g., [42,43]). In this method, UAV inspection is the main inspection technique, optical images are the primary data source, and deep learning is the data analysis method. Jenssen and Roverso [43] addressed the challenges of deep learning in vision-based power line inspection, such as lack of training data, class imbalance, and detection of small faults. A series of effective data augmentation techniques were applied to balance out the imbalanced classes. A multi-stage component detection and classification was proposed based on the single-shot multi-box detector and deep residual networks for fault identification. Field test results indicated that the proposed approaches could address the challenges and deliver significant improvement for detecting and classifying power line components. Thus, it is evident from the literature that UAV-based improved inspection techniques possess a promising potential for safe and efficient condition assessment of crossarms.

7. Strengthening Methods for In-Service Crossarm and Alternate Crossarm Types

Strengthening of the existing crossarms that are reaching the end of their service life is an economical solution instead of using replacements. Moreover, strengthening has sustainable aspects, considering the limited resources consumed, in comparison with crossarm replacement. Shahi [29] investigated the feasibility of strengthening wooden crossarms using glass-fibre-reinforced polymer (GFRP) wrap. The regions of crossarms subjected to higher stresses were wrapped using GFRP and the mechanical performances of these strengthened crossarms were evaluated using experiments. There were significant improvements of the MOR of strengthened crossarms in comparison with reference specimens.

National standards on crossarms specify the relevant timber species to be used in producing crossarms considering the strength and durability ratings. Some researchers have explored employing native timber species with lower durability ratings to be used as crossarms by improving the durability through coating with resins (e.g., [44,45]). The resin-coated crossarms exhibited improved mechanical and durability properties, complying with the national standard specifications. The native timber species found in abundance can be utilised in crossarm production with the use of this method as a solution for the increased cost of conventional timber species used in crossarm production.

Instead of using solid sawn timber for crossarms, laminated timber also can be utilised effectively, given that a good quality control is ensured in the manufacturing process to ensure proper bonding between the laminates. Mechanical testing has shown that both horizontally and vertically laminated timber crossarms possess sufficient strength requirements according to the specifications [30]. The laminated crossarms made from decommissioned CCA-treated timber poles have also exhibited adequate mechanical and acoustic properties [46]. This can address the longstanding issue of recycling the condemned CCA-treated timber poles, since CCA is a hazardous material which is to be used with caution.

Commonly used alternate material for timber crossarms is fibre-reinforced polymer (FRP). FRP is a relatively lightweight material with reasonable strength characteristics. Researchers have paid attention to exploring different characteristics of FRP as an alternative material for crossarms (e.g., [47–49]). Fibreglass crossarms were found to have greater lightning power strength compared to wood crossarms [50]. Considering the mechanical, thermal, electrical, and durability properties, fibreglass crossarms have a good capability to replace conventional timber crossarms [51]. Long-term creep behaviour of crossarms has been investigated by researchers to better understand the mechanical performance of these assets over their service life. Asyraf et al. [52] explored conceptual designs of creep testing rig for full-scale composite crossarms using the integration of theory of inventive problem-solving (TRIZ), morphological chart, and analytic network process (ANP). The challenges in the design of creep testing machine and improving criteria for current testing apparatus were also presented. Comparison of long-term creep behaviour of glass-fibre-reinforced polymer (GFRP) and Balau crossarms was carried out by Asyraf et al. [53]. The creep properties of Balau wood and pultruded composite at load of 10, 20, and 30% of ultimate flexural stress were evaluated from quasi-static flexural test results. The GFRP specimen exhibited high creep resistance with greater stability during transition from elastic to viscoelastic phase. It was concluded that pultruded GFRP composite crossarms had adequate durability considering the creep response. Alhayek et al. [54] investigated the effects of stacking sequence for the flexural creep behaviour of pultruded GFRP composite crossarms. Four-point bending creep experiments were performed at three distinct stress levels of the ultimate flexural strength to study the creep behaviour of distinct stacking sequences. The experimental results indicated that the stacking sequence of GFRP composite crossarms has a substantial effect on the creep behaviour in terms of the reduced flexural modulus modelled using Findley's power law.

8. Conclusions

Safe, reliable, and uninterrupted power distribution for the end users is the ultimate goal of power distribution networks. To achieve this, accurate structural condition assessment of the crossarms is of utmost importance. This paper provided a summary of the health monitoring techniques adopted for crossarms. The conventional inspection techniques, improved inspection methods employing UAVs, and advances in NDT techniques were reviewed, outlining the relative advantages and disadvantages. In addition, the decay identification and flexural strength assessment of crossarms were discussed, referring to the previous works. Bending test results for 110 Australian timber crossarms were presented, along with the analysis. Further, the studies on crossarm strengthening and alternate crossarms were reviewed. On the basis of the conducted review, the following conclusions can be made.

- The conventional crossarm inspection techniques provided subjective results relying on the experience of the inspector, and thus the reliability of the obtained results was questionable.
- The improved inspection techniques using unmanned aerial vehicles and other non-destructive testing methods were capable of conducting an accurate condition assessment of in-service crossarms. Nevertheless, most of these techniques required post-processing, compromising the ease of obtaining results.
- Each condition assessment technique was found to have added advantages as well as limitations and shortcomings. Thus, it can be concluded that for an effective, accurate, and reliable condition assessment system for crossarms, an integrated approach is required, combining the conventional inspection methods, improved inspection techniques, and non-destructive testing techniques. Integrated approaches can be complemented with artificial intelligence to develop automated condition monitoring of crossarms.

Based on the highlighted relative advantages and disadvantages of each condition assessment technique, power network managers can decide on the most suitable technique for a particular network considering the aspects of available resources, simplicity of operation, time, cost, and the required level of accuracy. With large numbers of in-service assets and their condition assessment data obtained over the service life, databases need to be maintained to decide on replacements and to make other management decisions. Thus, future research can be directed toward artificial intelligence and machine learning algorithms with integrated condition assessment approaches for crossarms.

Author Contributions: Writing, review and editing, P.R., S.B., E.G. and J.S. Supervision, P.R. and E.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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