AN ABSTRACT OF THE THESIS OF

Larry Ostman for the degree of Master of Science in Forest Products presented on May 2, 1985.

Title: Development of Techniques to Study the Behavior of Bolted Wood Joints

Abstract approved

Dr. Philip Humphrey

The design of bolted wood joints has, to date, been primarily based on empirical work. Much of this has been on single bolted joints. The extrapolation of this data to cover multiple bolted and large diameter bolted joints is questionable. There appears to be a lack of basic understanding of the behavior of bolted wood joints as they are loaded to failure. This thesis is concerned with the development of two techniques that may be used to gain a better understanding of bolted joint behavior.

The first technique involves the use of wood wafers or lamina which provide a two dimensional representation of a bolted joint during loading. It involves mounting a specially cut thin section of wood between two glass plates with a steel pin representing a bolt passing through the resultant wood glass sandwich. The approach is used to observe the wood deformation around the bolt in a plane normal to the bolt axis. It may also be used to simulate
multiple bolted joints.

The third dimension of the joint (in the axial direction of the bolt) is added by the second technique. This consists of taking x-ray scans of complete joints as they are loaded to failure. The bending behavior of bolts and associated wood deformation as they are effected by a range of joint parameters may be quantified in this way. The development and numerical integration of these two techniques will, it is hoped provide means to obtain a clearer three dimensional understanding of the behavior of bolted wood joints.
Development of Techniques to Study the Behavior of Bolted Wood Joints

by

Larry Ostman

A THESIS

submitted to

Oregon State University

in partial fulfillment of the requirements for the degree of

Masters of Science

Completed May 2, 1985

Commencement June 1985
APPROVED:

Assistant Professor of Forest Products in charge of major

Head of department of Forest Products

Dean of Graduate School

Date Thesis is presented May 2, 1985

Typed by Penny Williams for Larry Ostman
ACKNOWLEDGMENTS.

The technical and nontechnical assistance of my major professor, Philip Humphrey, is greatly appreciated.

I would like to thank Ralph and Margret Hull for their support and the donation of testing material.

I would also like to thank my parents for their support, patience, and understanding.
TABLE OF CONTENTS

CHAPTER I - INTRODUCTION ............................................. 1

CHAPTER II - DISCUSSION OF SELECTED LITERATURE ................. 6

CHAPTER III - EXPERIMENTAL PROCEDURES ......................... 15
  3.0 Introduction .................................................. 15
  3.1 The Two Techniques and Their Interaction Outlined ......... 16
     3.1.1 Technique I: The Wood Laminar Approach ............ 17
     3.1.2 Technique II: X-ray Scanning of Complete Joints During Loading 19
     3.1.3 Combination of Techniques I and II .................. 21
  3.2 The Wood Laminar Approach: Experimental Details .......... 21
     3.2.1 Apparatus Design ...................................... 21
     3.2.2 Wood Material Selection and Preparation .......... 28
     3.2.3 Procedures ........................................... 29
     3.2.4 Data Collection ...................................... 33
  3.3 Monitoring Bolt Bending Within Joints: Experimental Details 36
     3.3.1 The System For Joint Loading and X-ray Scanning .... 37
     3.3.2 Materials Used in the X-ray Scanning Approach ...... 40
     3.3.3 Procedure for the X-ray Scanning Approach ........ 42
     3.3.4 Data Collection ...................................... 44
  3.4 Experimental Design .......................................... 48

CHAPTER IV - DATA REDUCTION .......................................... 52
  4.0 Introduction .................................................. 52
  4.1 Reduction of Data From Wood Laminar Technique ............. 52
     4.1.1 Elongation Correction ................................ 53
     4.1.2 Correction of Load Values for Friction ............ 54
     4.1.3 The Corrected Load-Slip Curves ...................... 57
  4.2 Reduction of Data From the X-ray Technique ................. 60
     4.2.1 Data Retrieval from X-ray Scans ..................... 60
4.2.2 Construction of a Bolt Curvature Graph
4.2.3 Averaging of Whole-Joint Load-Slip Curves
4.3 Intergration of the Techniques to Determine Load Distribution

CHAPTER V - DISCUSSION OF RESULTS AND TECHNIQUES
5.0 Introduction
5.1 Behavior of "Standard" Joint Configuration
  5.1.1 Observations from the Wood Laminar Technique
  5.1.2 Behavior of Joint: X-ray Scanning
5.2 The Effects from Selected Variables on Joint Behavior
  5.2.1 End Distance Effect
  5.2.2 Bolt Diameter and L/D Ratio
  5.2.3 Grain Orientation
  5.2.4 Flatted Bolts
  5.2.5 Natural Defects in the Area of the Bolt
  5.2.6 Multiple Bolt Simulation

CHAPTER VI - CONCLUSIONS AND RECOMMENDATIONS
6.0 Introduction
6.1 Conclusions
  6.1.1 Wood Laminar Technique
  6.1.2 X-ray Technique
  6.1.3 Combining the Techniques
6.2 Recommendations for Future Research Using These Techniques

BIBLIOGRAPHY

APPENDIX
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>A typical three member double shear bolted tension joint.</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>End and edge distances defined</td>
<td>2</td>
</tr>
<tr>
<td>3.1</td>
<td>The bolted joint configuration adopted as a standard for the present investigation.</td>
<td>17</td>
</tr>
<tr>
<td>3.2</td>
<td>The principle of the wood laminar approach represented diagrammatically.</td>
<td>18</td>
</tr>
<tr>
<td>3.3</td>
<td>The principle of the x-ray scanning method used to monitor progressive bolt bending on complete joints.</td>
<td>20</td>
</tr>
<tr>
<td>3.4</td>
<td>A frontal view of the wood wafer testing arrangement.</td>
<td>22</td>
</tr>
<tr>
<td>3.5</td>
<td>Elevations and sections of the brass supporting framework.</td>
<td>24</td>
</tr>
<tr>
<td>3.6</td>
<td>Cross section of circular steel pin used in this investigation.</td>
<td>26</td>
</tr>
<tr>
<td>3.7</td>
<td>Friction grips used to attach wood wafer to crosshead.</td>
<td>28</td>
</tr>
<tr>
<td>3.8</td>
<td>Exploded view of wood laminar testing frame.</td>
<td>31</td>
</tr>
<tr>
<td>3.9</td>
<td>The order of screw tightening of testing frame.</td>
<td>32</td>
</tr>
<tr>
<td>3.10</td>
<td>The arrangement for illuminating the specimen and taking time lapse photographs during testing.</td>
<td>34</td>
</tr>
<tr>
<td>3.11</td>
<td>A typical uncorrected load-displacement plot from wafer testing.</td>
<td>35</td>
</tr>
<tr>
<td>3.12</td>
<td>Typical output for friction tests on wafers (no pin included).</td>
<td>36</td>
</tr>
<tr>
<td>3.13</td>
<td>X-ray testing frame inside lead lined x-ray box.</td>
<td>38</td>
</tr>
<tr>
<td>3.14</td>
<td>Design of test frame for whole-joint loading.</td>
<td>39</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.15</td>
<td>Location of glue lines and reference pins in main and side members of the standard joint.</td>
<td>41</td>
</tr>
<tr>
<td>3.16</td>
<td>Typical load slip curve from x-ray tests.</td>
<td>45</td>
</tr>
<tr>
<td>3.17</td>
<td>A partial set of x-ray scans corresponding to load slip trace of figure 3.16.</td>
<td>46</td>
</tr>
<tr>
<td>3.18</td>
<td>Specification of multiple bolt configurations used in the wood laminar technique.</td>
<td>51</td>
</tr>
<tr>
<td>4.1</td>
<td>A typical slide of wafer deformation showing where actual slip values are extracted.</td>
<td>54</td>
</tr>
<tr>
<td>4.2</td>
<td>A typical friction load-slip curve for wood wafer between glass plates.</td>
<td>55</td>
</tr>
<tr>
<td>4.3</td>
<td>A typical load-slip curve from a standard wafer test with pin included.</td>
<td>56</td>
</tr>
<tr>
<td>4.4</td>
<td>A load-slip curve corrected for frictional load and distortion of testing apparatus.</td>
<td>58</td>
</tr>
<tr>
<td>4.5</td>
<td>Replications of corrected load-slip curves for three end distances.</td>
<td>59</td>
</tr>
<tr>
<td>4.6</td>
<td>Locations of the five displacement measurements taken along the length of the bolt.</td>
<td>61</td>
</tr>
<tr>
<td>4.7</td>
<td>Scatter plots of localized bolt displacements at various positions along the bolt.</td>
<td>65</td>
</tr>
<tr>
<td>4.8</td>
<td>Averaged curves of localized slip versus total joint slip for various positions along the length of the bolt.</td>
<td>66</td>
</tr>
<tr>
<td>4.9</td>
<td>Graphical representation of bolt curvature for various levels of total joint slip.</td>
<td>67</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.10</td>
<td>Typical load-slip trace from x-ray technique.</td>
<td>68</td>
</tr>
<tr>
<td>4.11</td>
<td>Average of 5 load-slip traces of standard joint tests from x-ray technique.</td>
<td>69</td>
</tr>
<tr>
<td>4.12</td>
<td>Idealized load-slip curve from wood laminar technique.</td>
<td>71</td>
</tr>
<tr>
<td>4.13</td>
<td>Actual displacement of bolt into wood material.</td>
<td>72</td>
</tr>
<tr>
<td>4.14</td>
<td>Modeled load distribution along the length of the bolt at a total joint slip of 4 mm.</td>
<td>73</td>
</tr>
<tr>
<td>5.1</td>
<td>First photograph in a series from a typical radial wood wafer test.</td>
<td>75</td>
</tr>
<tr>
<td>5.2</td>
<td>Typical corrected load-slip curve from wood laminar technique.</td>
<td>76</td>
</tr>
<tr>
<td>5.3</td>
<td>Photographs for a typical test run on a radial section.</td>
<td>77</td>
</tr>
<tr>
<td>5.4</td>
<td>A schematic showing general zones of deformation around bolt</td>
<td>79</td>
</tr>
<tr>
<td>5.5</td>
<td>Overall view of failed radial test specimen.</td>
<td>81</td>
</tr>
<tr>
<td>5.6</td>
<td>Photographs for a typical test run using tangentially cut wafers</td>
<td>82</td>
</tr>
<tr>
<td>5.7</td>
<td>Visual comparison of compression failure from x-ray and wood laminar techniques.</td>
<td>87</td>
</tr>
<tr>
<td>5.8</td>
<td>The constructed load distribution curve along the bolt</td>
<td>89</td>
</tr>
<tr>
<td>5.9</td>
<td>Joints of conventional and modified design</td>
<td>90</td>
</tr>
<tr>
<td>5.10</td>
<td>Comparison of bending characteristics of bolts with L/D ratios of 6 and 12.</td>
<td>94</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5.11</td>
<td>Series of photographs of test done with a flatted pin.</td>
<td>96</td>
</tr>
<tr>
<td>5.12</td>
<td>Series of photographs of a wafer with a knot included.</td>
<td>98</td>
</tr>
<tr>
<td>5.13</td>
<td>Failed wafers of the multiple bolt configurations tested.</td>
<td>99</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.1</td>
<td>Replications and wood orientation of friction tests done on the wood laminar technique.</td>
<td>49</td>
</tr>
<tr>
<td>3.2</td>
<td>Tests and replications on wood wafers using a single bolt.</td>
<td>49</td>
</tr>
<tr>
<td>3.3</td>
<td>Tests of multiple bolt configurations done on the wood laminar technique.</td>
<td>50</td>
</tr>
<tr>
<td>3.4</td>
<td>Tests and replications of x-ray scanning of complete joints loaded to failure.</td>
<td>50</td>
</tr>
<tr>
<td>4.1</td>
<td>A sample of resultant data extracted from x-ray images.</td>
<td>63</td>
</tr>
<tr>
<td>A.1</td>
<td>Replication 1</td>
<td>108</td>
</tr>
<tr>
<td>A.2</td>
<td>Replication 2</td>
<td>108</td>
</tr>
<tr>
<td>A.3</td>
<td>Replication 3</td>
<td>109</td>
</tr>
<tr>
<td>A.4</td>
<td>Replication 4</td>
<td>109</td>
</tr>
<tr>
<td>A.5</td>
<td>Replication 5</td>
<td>109</td>
</tr>
</tbody>
</table>
DEVELOPMENT OF TECHNIQUES TO STUDY THE BEHAVIOR OF BOLTED WOOD JOINTS

CHAPTER I - INTRODUCTION

The bolted connection is an important type of mechanical fastener used in timber structures. To date, design specifications for such joints between structural members have been based primarily on empirical laboratory testing of joints incorporating single bolts. Factors affecting the behavior of even these relatively simple joints are not well understood. Furthermore, most structural connections involve the use of multiple bolts. When the results of tests on single bolted joints are extrapolated to include the more complex multiple bolt configurations, still more assumptions have to be made.

This thesis is concerned with the design of structural joints which are loaded in tension parallel to the grain of the wood members. One of, if not the main, configuration of joint used in such situations, consists of three members in a double shear arrangement. This is represented in Figure 1.1. This balanced configuration is extensively used in structural systems which may incorporate either solid or laminated timbers. A single bolt may be used to act as a pin connector, or more commonly in present building practices, multiple bolts are used. This is often to impart higher tensile strengths to joints between relatively narrow members.
Figure 1.1 A typical three member double shear bolted tension joint.

Bolt positions within the joint are usually specified using two terms. End distance is used to describe the distance between the center of the bolt and the end of the joint members, while the distance from the center of the bolt to the edge of a member is the edge distance (Figure 1.2).

Figure 1.2 End and edge distance defined. These are commonly specified in multiples of the bolt diameter.
1.2). The present design requirements (National Design Specifications, 1982) these distances are specified in multiples of the bolt diameter used. The distances between bolts in a multiple bolt joint are also specified in terms of bolt diameters.

Presently accepted design specifications state that side members should be half the thickness of the main member and of the same quality of material. Metal side plates may be used, and often are, in place of wood. This significantly increases allowable loads for many joint arrangements. The amount of this increase has sparked some controversy within the engineering community of late. In the latest edition of the National Design Specifications (1982) allowable design values have been increased from the previously accepted value of 25% to a new value of 75% above specified values for the all-wood arrangement. Controversy about the safety of such an increase has led the present researchers to adopt a more broadly based research approach and hence the development of the techniques described here in. The metal side plate issue is now just one of number of design factors that have been highlighted as being in need of in-depth analysis.

A purpose of these design criteria is to promote a preferred type of failure. Short end distances, for example, may cause the end of the joint member to fail in shear. A small edge distance however, may cause tension failure in the wood material on either side of the bolt.
hole. The latter are not the preferred modes of failure. An increase in the propensity for compression failure of wood material immediately around the bolt appears to lead to superior performance. In this situation, even after some localized deformation of the wood material has occurred, the joint can still support a significant load. The mechanics that affect these characteristics of the joint are rather complex - being a combination of wood material deformation and failure, and bolt flexure. Together, these cause a non-uniform distribution of load sharing across the width of the joint.

The present work is directed towards developing techniques which will enable a better understanding of bolted wood joint behavior to be gained. This is with a view to optimizing designs in the future. The work involves devising a combination of two approaches which have both long term rigorous and shorter term applied applications. These will jointly provide an understanding of material behavior and component interaction within a joint configuration which has been adopted as a standard for this study. Following this, the techniques may be used as tools to carry out sensitivity studies for the numerous interactive variables that constitute joint design and affect performance. This should reduce the need for costly, time consuming and somewhat limited trial and error tests on full size joints.

The first technique is used to quantify wood material
deformation and failure that occurs around the bolt as loading progresses. A two dimensional though highly specific view of the cross sections of the joint is gained by developing a thin wood wafer approach. The second and complimentary technique is used to see how bolts bend in the joint during tensile loading. This is done by taking a series of x-rays of corresponding whole bolted joints as they are progressively loaded to failure. Combination of these approaches will enable a three dimensional understanding of joint behavior during loading to failure to be gained. This thesis is directed towards the development of these techniques. Investigations to follow will use these as tools for joint improvement. For this reason, experimental results presented here are not extensive and analysis is only included to demonstrate potential applications of the techniques in future studies.

A note about units of measurement may be appropriate here. To simplify analysis, System International (SI) units will be used throughout this work. Bolt and joint dimensions are, however, multiples and simple fractions of inches. This is only to enable comparisons to be made with the results of previous workers who mainly worked in inches.
CHAPTER II - DISCUSSION OF SELECTED LITERATURE

There are a number of mechanical fasteners and connectors used in the wood construction industry today. These include common nails, truss plates, staples, and screws. These are primarily used in light frame construction. For larger structures, shear plates and toothed and split ring connectors are often used in conjunction with bolts. Bolts are also used without the addition of ring type components. The nature and use of these and other options for connection in many engineering situations are considered by Parmley (1977), while Stern's (1974) survey has been limited to connectors between wood members. This thesis is concerned solely however with bolted joints between wooden structural members that are loaded in tension parallel to the grain.

Much of the research carried out on the design of bolted joints has been empirically based. There has also been some theoretical work, though to date this has proved of limited value in practical applications. A selection of both the empirically and theoretically based approaches will be considered briefly here.

Some of the earliest work on bolted connectors was carried out by Trayer (1932). The results of Trayer's work are still used as a basis for the National Design Specifications (1977, 1982). In this pioneering work, several hundred joints of different configurations were tested to obtain an indication of safe working loads.
Results aided in establishing appropriate values for design factors such as bolt end and edge distances, spacing between bolts in multiple bolted joints, and member dimensions. Trayer's study involved the following variables which were investigated in factorial form:

- bolt diameter ranging from 1/4 inch to 1 inch
- five species of wood (Douglas-fir, southern yellow pine, sitka spruce, maple, oak)
- both wood and metal side members (otherwise referred to as splice plates)
- loading parallel and perpendicular to the grain
- main member thickness

Variation in member thickness leads to variation in length (L) to diameter (D) ratio for the bolts. The L to D ratio is widely defined as the length of the bolt within the main member (main member thickness), L, over the diameter, D, of the bolt. This ratio is a term commonly used and has been reported to have an effect on the bolt bearing stress of joints during loading.

Bolt bearing stress has been defined (Trayer, 1932) as the total load on the bolt, divide by its projected, or longitudinal cross sectional area (L x D) lying within the main member. This rather misleadingly assumes a uniform distribution of load along the length of the bolt. The bolt bearing stress at the proportional limit has widely been reported to decrease with increasing L to D ratio
Evidently, stress in non-uniformly distributed along the length of bolts within joints loaded in tension. Long and thin bolts lead to greater concentrations of stress at the interfaces between side and main members than do shorter, thicker bolts. This non-uniformity reflects the complexity of the interaction of components in the joint. Such complexity has led many workers to adopt descriptive approaches to design—sometimes based on inaccurate generalizations. Trayer (1932) suggested that the bolt bearing stress at the proportional limit remains constant among joints with equal L to D ratios. It was implied that the bolt bearing stress under a 1" bolt in an 8 inch main member loaded to the proportional limit is equal to the bolt bearing stress under a 1/2 inch bolt in a 4 inch main member.

This generalization is used to extrapolate design values for bolts larger than 1 inch in diameter. Testing of large diameter bolted joints is lacking and such a generalization may be unwarranted.

Bolt positioning and spacings recommended by the Wood Handbook (1955) and the National Design Specifications (1982) for joints loaded in tension parallel to the grain are as follows.

- End distance is specified to equal or exceed 7 bolt diameters for softwoods and 5 diameters for hardwoods.
- the edge distance shall be no less than 1 1/2 bolt diameters
- the spacing between bolts in a row shall not be less than four bolt diameters
- the spacing between rows shall not be less than 1 1/2 diameters of the bolt.

Some workers suggest that the end distance of seven diameters may be unnecessarily large (Snodgrass and Gleaves, 1960; Wilkinson, 1978). Snodgrass and Gleaves tested joints fabricated with a range of end distances and suggest that a value of four diameters would be acceptable, but recommended five diameters end distance to include an acceptable factor of safety. Wilkinson (1978) used moir'e fringe patterns and finite element analysis to study the stresses around a pin loaded hole. Based on this work, he suggests an end distance of 4 diameters. Wilkinson, in the same study, recommended a two diameter edge distance and between row spacing. This is more conservative than the 1 1/2 diameters recommended by the National Design specifications. The inconsistency in these recommendations serves to demonstrate our lack of basic understanding of the system. Most of the above conclusions are based on the results of tests using a single bolt. Wilkinson's work used 12.5 mm diameter bolts, while the work of Snodgrass and Gleaves was based on 12.5 mm and 19 mm diameter bolts. Extension of these results to other bolt diameters may not be justified.
When designing wood joints, using presently accepted rules, wood members are checked for load carrying capacity at the "critical net section". This term is defined as the cross sectional area of the member (normal to loading direction), less the projected area of wood material removed for the bolt holes. In practice, most bolted joints loaded parallel to the grain are designed to incorporate one or more parallel rows of bolts. Staggered bolt arrangements are discouraged. If such a configuration is used, then the net critical section is determined as if the bolts were in a parallel arrangement. This results in calculated values for critical net section being artificially low thereby unfairly reducing the calculated load carrying capacity of the staggered arrangement. Work done by Kunesh and Johnson (1968) indicates, however, that staggered bolt joints may have a greater load carrying capacity than normal in-line arrangements. It would seem logical to stagger the bolts to distribute shear forces across the joint. The techniques developed in this thesis will, it is hoped, enable more rational approaches to these design issues to be developed.

Allowable design loads for multiple bolt joints are presently derived from the product of the design for a single bolt, the number of bolts in the joint and a reduction factor for multiple bolts. This reduction factor is itself dependent upon: a) the number of bolts, b) cross sectional area of the main member, c) the ratio of the
cross sectional area of the main member to that of the side member and d) whether wood or metal splice plates are used. These reduction factors are based on work done by Cramer (1968) and Lantos (1969). It was found that there is an uneven distribution of load among bolts in a row. The two bolts at either end of the row each carry approximately 25% of the total load on the joint. This appears to be independent of the total member of bolts incorporated. Additional bolts only reduce the load on the interior bolts, but not on the outermost bolts. Other work (Wilkinson, 1980) indicates that the modification factors are adequate for predicting the "proportional limit" of the joint, but may over-estimate the ultimate strength. It should also be pointed out that the concept of proportional limit, so often adopted for bolted joints, is of questionable validity. Non-linearity of the whole load-slip characteristic of such joints is inevitable when one considers behavior of material within the system (this is considered in Chapter III).

More recent work (Wilkinson, 1983a, 1983b) indicates that any single bolt in a joint could carry a disproportional amount of the joint load. This work considers the random effects of individual bolt load-slip characteristics and the fabrication tolerances (hole positioning and clearances).

It has already been pointed out that when metal splice plates are used instead of wood the joint performance is
significantly increased (National Design Specifications, 1982; Mclain, 1981; Wood handbook, 1955; Trayer, 1932). In the 1977 National Design Specifications, the bolt design values could be increased by 25% when metal splice plates were used. This is in agreement with Trayer's (1932) work. The 1982 edition of the National Design Specifications incorporates a 75% increase for metal splice plates. This increase reflects data presented by Wilkinson (1980) and Mclain (1981). Wilkinson's data was collected from previous work done at the Forest Products Lab, Madison, Wisconsin. The data indicates that the increase may be more than 25%, but not as great as 75%. Wilkinson was not, however, investigating the effects of metal side plates, and did not make any conclusions to support a 75% increase. Mclain (1981) tested a number of joints with both wood and metal splice plates.

Here again, the limited number of arrangements tested and the fact that only half inch bolts were used severely limits the reliability of the conclusion to allow a 75% increase. Mclain concluded that a 25% increase in allowable load is justified, but that an increase in this value is not justified for all joint configurations.

Stress distributions around bolt holes have been considered by Wilkinson (1978a) and Stluka (1960). Most theoretical models have been restricted to idealized isotropic materials. Wilkinson did however attempt to model the stresses around a pin loaded hole in wood, an
anisotropic material. He investigated the stresses using finite element analysis and moir'e fringe patterns. These techniques represented a two dimensional, longitudinal cross section of a bolted joints. The dimension along the length of the bolt was not considered in this study. Present work suggests that this is a serious deficiency in many analyses. Wilkinson investigated how stress distribution is effected by edge and end distance, friction between the contact surfaces of the pin and hole, and the ratio of pin radius to hole radius. Wilkinson found good correlation between the results from the finite element analysis and the moir'e fringe patterns. The complexity of wood's structure does however limit the usefulness of these models. Vary limiting assumptions have to be made. Further refinement is needed before they may play a greater role in aiding in joint design. The finite element analysis was carried out using an iterative computer program. Due to the non-linearity of the problem, the computer time required to run the program proved to be cost prohibitive. This precluded its use to check stresses in multiple pins with diameters other than 1/2 inch. Wilkinson concludes that there is a significant change in the stress distribution with minor changes in the bolt to hole diameter ratio. Recommendations on reduced tolerances in bolt hole clearances were made in response to these findings. The present specifications require a 1/16 to 1/32 of an inch clearance. These values do not, according
to this study, enable the full potential for joint strength to be realized.

It has also been established that the quality of the bolt hole has a significant effect on the strength of a joint (Goodell and Phillips, 1944). In this work, it was suggested that joints with rough and fiberous bolt holes could have as much as a third the strength of joints with smooth holes. Smooth holes appear to give a more even distribution of load under the bolt than do rough ones.

There are many questions on how bolted wood joints should be designed to be efficient and also safe. Methods of evaluating and improving joint design are developed in this thesis. These techniques combine aspects of fundamental work with the advantage of experimental verification.
CHAPTER III - EXPERIMENTAL PROCEDURES

3.0 Introduction

Experimental techniques to address the issues raised in Chapters I and II are described here. The chapter begins with a restatement of the specific objectives of the investigation. Following this, the principles upon which the two main techniques developed in this work depend are introduced. Each technique is then dealt with in detail in terms of approach, apparatus, materials and procedure. Finally, a representatives set of data is presented for each method. Data reduction and interpretation will, however, be dealt with in Chapters IV and V to follow.

Testing of complete connection system has, to date, been the primary means of approaching design and design optimization. It is evident from Chapter II, however, that the behavior of even the simplest configuration is effected by a large number of interactive factors. Under these circumstances, a more rational approach to design would be to gain a better understanding of each factor and its effect on the system. Theoretical work based on numerical methods for stress-strain (or load-slip) analysis is providing some insight to this behavior. To date, however, the complexity of woods' structure has required assumptions to be made which limit the usefulness of the results of these techniques.

In an attempt to overcome the above difficulties with
empirical methods on the one hand and theoretical on the other, two complimentary experimental techniques have been developed here. These, it is considered, combine certain advantages of theoretical simulation with experimental methods. The objective is to develop techniques that could help in gaining a better understanding of material behavior within bolted joints during loading to failure. This is with a view to optimizing existing configurations and also developing new systems.

3.1 The Two Techniques and Their Interaction Outlined

One of the main difficulties in tackling structural bolted joint systems is their complexity in three dimensions. The circular shape of the bolt is alone sufficient to create complex behavior with the surrounding wood material. This complexity is compounded by the tendency of the bolt to bend during load application. These difficulties have been tackled here by adopting a two dimensional or laminar approach in the first method. This is in the planes perpendicular to the bolt axis. Information for the third and mutually perpendicular dimension (along the axis of the bolt) then forms the second and complimentary section of the work.

Before considering the approaches, the joint design itself will be introduced at this stage.

A simple double shear joint with a single bolt has
been adopted as a standard for this investigation. This configuration (12.5 mm diameter mild steel bolt into 75 mm x 75 mm main member and 37.5 mm splice plates) is shown below as figure 3.1.

![Figure 3.1. The bolted joint configuration adopted as a standard for the present investigation. Measurements are in millimeters.](image)

Two main factors have affected this choice of design. First, a sizable pool of experimental data has been accumulated on similar configurations by a number of researches (McClain, 1981; Stluka, 1960; Wilkinson, 1978). Second, the joint is manageable on available laboratory testing apparatus, while lying within the range of bolt and member sizes used in real life applications.

3.1.1 Technique I: The Wood Laminar Approach

The nature of wood material failures that occur
around the bolt are tackled here by considering deformations in a plane at right angles to the long axis of the bolt. The approach is represented diagramatically as figure 3.2 below. Wafers of wood measuring 0.8 mm in thickness are carefully cut from material equal in width and length to that of the central member of the joint shown in figure 3.1. Holes are drilled through the wafer pieces.
at a range of locations representing real bolted joint configurations. Each piece is dedicated to a single bolt hole position. The wafer to be tested is sandwiched between two glass plates with a specially profiled steel pin, representing a cross section of a bolt, included in the arrangement. The entire system is then mounted on the Instron Universal testing machine. Tensile loads are applied to the wood wafer via grips fitted to the crosshead, while the glasswood sandwich is suspended from the load cell above. Intense rear illumination of the wood around the steel pin exposes structural changes that occur in the material as it is loaded to failure. A stress-strain diagram is recorded for each test.

3.1.2 Technique II: Xray Scanning of Completed Joints During Loading

The two dimensional wafer approach is complimented by taking x-ray photographs of complete bolted joints systems during loading to failure. Progressive distortion (bending) of the bolt within the wood is quantified by taking approximately 10 x-ray scans during each test to failure. This approach is represented in figure 3.3 below.
Figure 3.3 The principle of the x-ray scanning method used to monitor progressive bolt bending on complete joints.
3.1.3 Combination of Techniques I and II

Integrating results from the two methods outlined above enables a three dimensional picture of the system to be formed. Slip values at any location along the bolt and at any stage in joint loading can be obtained from the x-ray scans. The nature of wood material failure at this level of deformation may then be ascertained by viewing the wood material failure mechanism from technique I.

Having outlined the principles upon which these techniques depend, each will now be described in detail in Sections 3.2 and 3.3.

3.2 The Wood Laminar Approach: Experimental Details

This technique depends on the glass creating a low friction and rigid boundary upon which the wood surfaces impinge. If this situation is approached, then the wood wafer will behave during loading as if part of a large body or continuum of wood on either side of the wafer surfaces. These requisites have been basic considerations during the design of the apparatus. The degree to which this situation is approached will be considered later in the manuscript.

3.2.1 Apparatus Design

The overall layout of the testing arrangement is shown below in figure 3.4. Each of the main components will be considered in turn.
Figure 3.4. A frontal view of the wood wafer testing arrangement
The testing frame:

A rigid metal frame is used to support the wood-glass sandwich arrangement and thereby support the simulated bolt. The system consists of two rectangular brass frames, each a mirror image of the other (see figure 3.5). The glass plates are recessed into the frames. Ten machine screws are used to hold the two halves together during the test. By controlling their tightness, uniform pressure across the wood surface is achieved. These screws are always tightened in the same order and to the same torque for each test. A specially designed torque wrench is used for this purpose. The inside bottom edge of each of the frames is recessed to make way for the wood wafer to pass through. The system is connected to the load cell by a 12.5 mm diameter steel pin which passes through both halves of the assembled frame. This aids in achieving axial alignment, a universal joint being included between the frame and load cell connector. The mass of the frame and glass system is in the order of 7.5 kg. This mass is offset on the recording system prior to forming a stress strain diagram.
Figure 3.3. Elevations and sections of the brass supporting framework.
The Glass Plates:

The material used to restrain the sides of the wood wafers had to be rigid, smooth, and clear. Transparency was needed to provide good, unimpaired visibility of the wood wafer in the vicinity of the pin. Smoothness was needed in order to minimize the frictional restraint on wood movement during loading. Rigidity was needed to ensure uniform pressure across the wood wafer and to support the steel pin. Glass thickness was quite arbitrarily selected in this work. Future development of this technique will involve a more rigorous approach to design, however. Ordinary plate glass, 6.25 mm (1/4" nominal) thick proved to be sufficient. Glass plates measuring 92 mm x 212 mm were obtained from a local supplier. Different pieces of glass were used for the various joint configurations investigated. Holes were drilled in pairs of glass plates to accommodate the steel pin. High accuracy was necessary to avoid misalignment of steel pin and holes in the pair of glass plates. The 6.25 mm diameter holes were drilled with a tungsten carbide bit lubricated with mineral oil.

The steel pin:

The steel pin represents a small axial portion of a bolt section. All work to date has been on 12.5 mm (1/2") diameter bolted joints. The end portions of pins are 6.5 mm (1/4") in diameter with a .8 mm thick by 12.5 mm (1/2")
diameter disk at the center (see figure 3.6). This central portion was machined to the same thickness as the wood wafer. If it were too thick, it would stop the glass plates effectively touching the wood. If it were too thin, then some wood could slip between the glass and the pin.
during testing. The diameter of the disc was such that there would be zero clearance between pin and wood wafer. Small changes in this has significant effect on failure mechanism (Wilkinson, 1982a). Bolt clearances will be the subject of future investigations using this technique.

The 6.5 mm diameter ends were fitted into the holes in the glass. This shape of pin was used to allow a clear view of the wood-pin interface. When holes are drilled in the glass, some chipping occurs around the edge. A 12.5 mm hole could have been drilled, but visibility would have been impaired. The pin was made of mild steel similar to that of the bolts actually used in the connectors being simulated.

Grips for wafer clamping:

The end of the test specimen, that protrudes out the end of the test frame, is attached to the cross head below by means of specially designed grips (see Figure 3.7). Provide uniform load transfer across the width of the wood wafer to avoid artificial forces and ensure uniaxial loading. This consist of two brass plates with friction pads glued to their inner surface. After some experimentation, 60 grit sand paper was found to provide the necessary load transfer. Two machine screws are used to clamp the grips to the wood. The original plans were to pass the machine screws through the test specimen. This
Figure 3.7 Friction grips used to attach wood wafer to crosshead

carved uneven load on the specimen during testing. The gripping of the wood wafers was therefore achieved entirely by friction.

Torque wrench:

In order to maintain constant friction between the glass plates and wood, a small torque wrench was specially designed and manufactured. A torque of .006 Nm was applied using the wrench.

Equipment associated with photographic recording of wood material failure during test will be described in section 3.2.4 dealing with data collection.

3.2.2 Wood Material Selection and Preparation

Material was selected to be as free from defects as possible and of low variability for the development of this
technique. Future work will include material representative of service conditions. All test specimens were cut from a 150 mm x 150 mm x 4.8 m piece of vertical grain, coastal Douglas-fir, timber. This was donated by Hull-Oakes Lumber Co., of Monroe, Oregon. The 4.8 meter timber was cut into 3 sections. These sections were machine dressed on radial and tangential surfaces. Veneers were sliced off these cants using the parallel or end slicing technique. This eliminated lathe checks and produced thin material of high surface quality. This was made possible by the cooperation of the Nicolia Door Company of Portland, Oregon. A thickness of 0.8 mm was selected as a compromise between machining limitations and the light penetration necessary for material observation during the test. Earlier attempts were made to cut specimens with a saw. This proved to be time consuming and did not yield material of the required surface quality.

The veneers were placed in a standard room and were allowed to stabilize to 12% MC. The material had a specific gravity of 0.51 at 12% MC and 8 rings per inch. After stabilizing, the veneer was cut to 75 mm x 430 mm.

3.2.3 Procedures

The testing procedures that were used were relatively simple to conduct. What follows is a description of the technique used for a standard testing sequence.
1. A hole was drilled in the test wood wafer specimen at the appropriate position. Holes were drilled at 1200 RPM using a bit that has a side cutting edge. The veneer was supported by blocks of wood during drilling. This produced a smooth, round hole.

2. The test specimen is assembled into the test frame in the following order (see figure 3.8): back frame, glass plate, steel pin, wood specimen, glass plate, front half of frame.

3. The ten machine screws are screwed in, but not tightened.

4. The test assembly is connected to the universal joint on the testing machine.

5. The bottom of the test specimen, which protrudes out of the frame, is placed in the bottom grips. The grips are tightened.

6. The ten machine screws are tightened with the torque wrench and in the same order for each test (figure 3.9).

7. An initial photograph of the bolt and wood material surrounding it is taken before the test is begun (see section 3.2.4).

8. Cross-head movement at a rate of 1 mm/min. is begun and is automatically recorded.

9. Three to four photographs are taken during the initial loading period where the stress strain curve is approximately linear. A hash mark is recorded on the
Figure 3.8. Exploded view of wood laminar testing frame.
stress strain curve where each photo is taken.

10. Other photographs are taken as compression failures and cracks appear within the portion of the wood wafer in
the vicinity of the bolt.

11. After catastrophic failure, (crack propagation and rapid fall in load) a final photograph is taken of the entire specimen. The field of view is enlarged for this photograph in order to include the cracks that propagate to the end of the specimen.

Catastrophic failure is considered to have occurred when the specimen can no longer sustain any significant load other than the friction between the glass and wood. The test specimen is removed from the frame, taped together, code numbered and saved. Not all specimens were photographed. For the remainder, load-deformation curves only, were recorded. A series of friction tests were carried out in this same manner. No photographs were taken. The tests were done without the steel pin. These tests were to determine the frictional forces between the wood and glass and to determine if they were fairly constant from test to test. This data was collected for correction purposes during data analysis.

3.2.4 Data collection

A series of photographs were taken as the specimen were loaded to failure. The photos were taken to record the modes of failure, and to give a clear and permanent record of the failure behavior.

A 35 mm camera was set up in front of the test frame. The field of view was approximately 80 mm x 106 mm. The
A steel pin was located near the bottom of the picture. Most wood failure occurs above this point. A 600 watt lamp was used to intensely illuminate the back of the specimen and pass through the wood. Densification zones and microcracks were clearly visible as the specimen was loaded. Compression failures appear as darkened areas in the wood. Illumination was from approximately a 60 degree angle above the pin (see figure 3.10). This was done to prevent a

Figure 3.10. The arrangement for illuminating the specimen and taking time lapse photographs during testing.
direct beam of light from entering the camera and overexposing the picture. A 100 watt light was also used to illuminate the front of the specimen. An aluminum shield with appropriate opening was used to reduce heating from the intense filament. Approximately ten color pictures were taken during each test. This photographic data will be presented in Chapter V. For each run, a load-displacement chart was produced on the Instron. A typical plot is shown as figure 3.11. Following this is a frictional calibration curve as figure 3.12. Correction of the load-deformation curve for friction will be carried out in chapter IV to follow.

**Figure 3.11** A typical uncorrected load-displacement plot during wafer testing.
3.3 Monitoring Bolt Bending Within Joints: Experimental Details.

The x-ray scanning method described here has been developed to determine how bolts deflect within joints during loading. This has provided data which may in future work be usefully integrated with information from the wood lamina technique. Complete joints of the form already shown in figure 3.1 are scanned periodically during their progressive loading to failure. Work to date has largely been directed toward development of the technique. For this reason, only a limited number of joint configurations have been investigated. These primarily involve the
standard configuration identified in section 3.1. Some tests have, however, been carried out using metal side plates of varying thickness, and bolt diameters other than 12.5 mm. Detail of the testing scheme used for this part of the work appear in section 3.4 which deals with experimental design for the whole project. This section will be limited to details of the technique itself.

3.3.1 The System for Joint Loading and X-ray Scanning

The overall layout of the approach is shown above as figure 3.3. For safety, the entire x-ray system and testing frame is contained in a lead lined box with work area measuring .34m x .45m x 1.18m. The x-ray source itself is a surplus model originally manufactured for dental work. A narrow slit beam of x-rays measuring approximately 2 mm x 90 mm, is produced by including a specially machined lead screen with a slot in the optical train. Entire scans of the bolt are produced by mechanically driving the x-ray unit across the loaded joint. Specially selected film is positioned below the joint to record profiles of the bolts. A new piece of film is placed under the joint for each scan as tensile leads are incremental applied. Figure 3.13 below shows the testing frame and joint within the lead lined box.
The testing frame:

The x-ray apparatus imposed some challenging limitations on the frame design because of the restricted space available inside the lead lined box. The frame had to be sufficiently rigid to apply loads in the order of 65 kN in a controlled fashion while also enabling slip, load and bolt bending (by scanning) to be recorded.

The main member of this testing frame was a 100mm by 200mm steel I-beam .6 m long. The device is diagrammed as figure 3.14 below. The yoke is welded to the I-beam and holds the main member of the joint with a 25 mm diameter
Figure 3.14  Design of the test frame for whole-joint loading.
steel pin. At the other end of the beam is a pressure plate. A 25 mm diameter steel rod passes freely through this plate. At one end of the rod is a steel block which is used to transfer load from the testing frame via the splice plate to the joint itself. Attached to the other end of this rod is the load cell and backing plate. The backing plate is used to transfer load onto the joint. This is achieved by using two loading screws which are threaded into the backing plate and push against the pressure plate. Turning the loading screws clockwise pushes the two plates apart, thus transferring load onto the joint. The load cell was a Strainsert, universal flat load cell of 11 kN capacity.

Relative movement between the central and side members of the joint during loading was measured using a D.C. linear voltage displacement transducer (LVDT) with a 13 mm displacement range. The load and slip was recorded on a x-y recorder.

Machined into the side of the I-beam was a 6 mm by 120 mm slot. This provided access to enable the x-ray film packet to be positioned directly under the bolt being tested.

3.3.2 Materials Used in the X-ray Scanning Approach

Joints tested were of the form outlined in figure 3.1. Test specimens were of coastal Douglas-fir, cut from a 200 mm x 1.1 m glue laminated beam. A 2 meter section of beam
was donated by Weyerhaeuser Co., Laminating Division, Cottage Grove, Oregon. Main members were cut from the beam to approximately 90 mm by 110 mm by 450 mm. These were then reduced to 75 mm by 75 mm such that two glue lines were centered in the specimen. (Figure 3.15). Ten pairs of specimens were side matched for tests using wood splice plates. Material from the outer laminations of the glue-lam beam were not used since they were of different lumber grade. The wood splice plates were cut 38 mm x 75 mm with a glue line located at the center. (Figure 3.15) This was done to avoid locating a glued surface at the shear plane between members. Such a situation could alter the frictional coefficient between main member and side plates.

![Diagram of glue lines and reference pins](image)

**Figure 3.15** Location of glue lines and reference pins in main and side members of the standard joint.
Metal splice plates were also used. These were of mild cold rolled steel with thicknesses of 12.8 mm, 6.4 mm, and 2.0 mm. One set of 12.8 plates and two sets of 6.4 mm plates were used. The bolt holes for the 6.4 mm plates were only used once. New holes would be drilled and the end of the plate cut off for each new test. The 2 mm plates were only used once.

3.3.3 Procedure for the X-ray Scanning Approach

No separation will be made in this section between general procedures and methods of data collection.

Joint preparation and assembly:

Bolt holes in the 75 mm x 75 mm x 450 mm test specimens were made with a drill bit that had a side cutting flute. This produced a clean smooth hole. In the present work the bolt holes were only drilled 7 bolt diameters from the end of the specimen. Future studies may investigate the effect of end distance on bolt bending. A 25 mm diameter hole was drilled 180 mm from the other (supporting) end. This provided 165 mm between the bolt hole and the hole used to mount the test specimen into the testing frame. The wood splice plates were drilled in the same manner.

Small steel reference pins were then positioned in the wood members, and/or attached to metal splice plates. These appear on the x-ray scans, and the displacement
between main member, splice plates and bolts can be measured from them. In the main member and wood splice plates, the pins were driven 16 mm from the center of the bolt hole and on the unstressed side (figure 3.15). The reference pins for the metal splice plates were taped to the plates, so as to protrude outwards from the main member. Figure 3.15 shows the location of the reference pins.

The joints were carefully assembled in order to ensure good joint alignment. The nuts were initially tightened before being backed off and finally hand tightened. All joints were tested in this manner using finger tight nuts. Washers were used on the wood splice plates in order to provide support for nut and bolt heads.

Testing procedures:

What follows is a step by step description of the procedure for joint testing.

1. The assembled joint was mounted on the I-beam. Care being taken to ensure the two holding pins, bolt and load cell were aligned.

2. An envelope containing the x-ray film was placed beneath the bolt.

3. The complete test frame was positioned under the x-ray head to scan either the back or front half of the joint. This was done because the beam was not wide enough to scan the entire length of the bolt in one pass. The
joint was then scanned.

4. The test frame was moved to scan the second half of the joint. This two stage scanning is done for each x-ray photograph taken.

5. The x-y plotter was zeroed and pen engaged

6. The x-ray film is removed and a new sheet is inserted

7. The two loading screws were turned alternately a 1/4 turn at a time. When approximately .3 mm of slip was measured the loading was stopped.

8. The joint was allowed to stand for 3 minutes. This was sufficient to allow the stress relaxation rate to have fallen to a satisfactorily low level.

9. The second x-ray scan was then taken. A hash mark was placed on the stress strain curve to indicate when the scans were taken.

10. Steps 6 to 9 were repeated until catastrophic failure of the joint occurred. X-ray scans were taken at slips of approximately: 0.3 mm, 0.6 mm, 1.2 mm, 1.8 mm, 5 mm and then every 2 mm of additional slip. Catastrophic failure was considered to have occurred when the specimen could no longer sustain a significant load.

11. A last x-ray scan was taken after catastrophic failure. This corresponded to a no-load situation.

3.3.4 Data Collection

The x-y recorder was used to record a stress strain
curve for the joint. A typical stress strain curve is shown as figure 3.16. The shape of this curve is discussed in Chapter 4. A corresponding set of x-ray scans are shown as figure 3.17.

![Stress-Strain Curve](image)

**Figure 3.16** A typical load-slip curve from the x-ray tests. Letters a to d correspond to x-rays in figure 3.17 and o's correspond to other x-rays taken but not shown.
Figure 3.17 A partial set of x-ray scans corresponding to the load slip curve of figure 3.16.
3.4 Experimental Design

The purpose of this project has been to develop experimental techniques which may be used as tools in future investigations. For this reason, detailed experimental design including specific parameters to be measured and levels of replication could not be specified at the beginning of the work. The number of variables that influence joint performance are considerable. The approach has therefore been to select one, or a limited range of combinations of parameters with a view to collecting data sufficient only to demonstrate the usefulness of the approaches. Even with this limitation, the results already obtained have shed new light on the behavior of joints.

In the case of the wood lamina technique, 12.5 mm diameter bolts into .8 mm wide material (main member) has been simulated throughout. A limited range of bolt positions together with preliminary trials with multiple bolted systems have, however, been included. In the case of the x-ray scanning method, most tests were carried out using 12.5 mm diameter bolts, though a limited range of bolt diameters and side plate types (both wood and metal) were investigated. Again it should be emphasized that these tests were of a preliminary nature. Levels of replication in future work will to be amended in the light of variability detected here.

Experimental design information is shown in tables 3.1 to 3.4. Diagram of multiple bolt configurations used in
the wood laminar technique are shown in figure 3.18.

Table 3.1 Replication and wood orientation of friction tests done on the wood laminar technique. (bolt not included):

<table>
<thead>
<tr>
<th>Ring orientation</th>
<th>Replication</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-) radial</td>
<td>10</td>
</tr>
<tr>
<td>(-) tangential</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.2 Tests and replications on wood wafers using single bolts.

<table>
<thead>
<tr>
<th>End distance (bolt diameters)</th>
<th>Ring orientation in wafer</th>
<th>Photograph* (#)</th>
<th>Replications (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3d (37.5 mm)</td>
<td>radial</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3d (37.5 mm)</td>
<td>tangential</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>5d (62.5 mm)</td>
<td>radial</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>5d (62.5 mm)</td>
<td>tangential</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>7d (87.5 mm)</td>
<td>radial</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>7d (87.5 mm)</td>
<td>tangential</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>9d (112.5 mm)</td>
<td>radial</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>9d (112.5 mm)</td>
<td>tangential</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>11d (137.5 mm)</td>
<td>radial</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>11d (137.5 mm)</td>
<td>tangential</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

* Photograph (#) is the number of replications photographed not the number of photos taken.
Table 3.3 Tests of multiple bolt configurations investigated using the wood laminar technique.

<table>
<thead>
<tr>
<th>Number of bolts</th>
<th>Configuration*</th>
<th>Ring Orientation</th>
<th>Replication (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>x x x</td>
<td>radial</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>x x x</td>
<td>radial</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>x x x</td>
<td>radial</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: See Figure 3.19 for details of multiple bolt configurations. All other variables used in these tests in the above tables are as described in sections 3.1 and 3.2.

Table 3.4 Tests and replications for x-ray scanning of complete joints loaded to failure.

<table>
<thead>
<tr>
<th>Bolt diameter (mm)</th>
<th>Side plate type</th>
<th>Side plate thickness (mm)</th>
<th>Replication (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5 mm</td>
<td>wood</td>
<td>37.5 mm</td>
<td>8</td>
</tr>
<tr>
<td>12.5 mm</td>
<td>mild steel</td>
<td>12.5 mm</td>
<td>6</td>
</tr>
<tr>
<td>12.5 mm</td>
<td>mild steel</td>
<td>6.3 mm</td>
<td>6</td>
</tr>
<tr>
<td>12.5 mm</td>
<td>mild steel</td>
<td>2.0 mm</td>
<td>6</td>
</tr>
<tr>
<td>9.2 mm</td>
<td>mild steel</td>
<td>6.3 mm</td>
<td>4</td>
</tr>
<tr>
<td>6.3 mm</td>
<td>mild steel</td>
<td>6.3 mm</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: All other variables used in these tests are as described in Figure 3.1, section 3.7.
Figure 3.18 Specifications of multiple bolt configurations used in the wood laminar technique. Dimensions are in millimeters.
CHAPTER IV - DATA REDUCTION

4.0 Introduction

Much descriptive information and numerical data has already been derived from both the wood laminar and the x-ray techniques. The main objective of this thesis has, however, been the development of these techniques rather than in depth analysis of derived data. In the planning stages of the work, the techniques were developed with the main objective of gaining a better qualitative understanding of the behavior of joint systems. It has now become evident however, that quantitative analysis and modeling methods may also be justified. The latter will be the subject of studies to follow.

Reduction of a representative set of raw data will be demonstrated here to enable a discussion of the basic trends to be included in Chapter V. The laminar technique will be considered first. This will be followed by the x-ray technique and finally how reduced data from the two sources may be combined to derive a three dimensional understanding of joint behavior.

4.1 Reduction of Data From the Wood Laminar Technique

Data derived from this technique is produced in two forms: sets of photographic slides taken of the wood deforming around the steel pin as loading progresses, and the corresponding load-slip traces from the whole wafer
during such loading. The numerical data and its analysis will be discussed here while interpretation of visual (photographic) information will be included in Chapter V to follow.

The load-slip traces provide an indication of the strength and stiffness of the two dimensional bolt configuration being tested. Certain corrections to this raw data are however necessary.

4.1.1 Elongation Correction

The strain axis of the traces have to be corrected for elongation of the testing frame and external connections since the displacements recorded are for the cross head and not the actual localized movement of the wafer around the steel pin. Reliable values for the actual slips may be obtained by projecting the slides onto a screen where the displacements may be inferred by scaling off from the known diameter of the pin. The displacements are measured between the pin edge and the undamaged edge of the hole in the wafer (see figure 4.1 below). Knowing the stage during the loading cycle at which each slide was taken enables corresponding load values to be obtained for each slip value.
Figure 4.1 A typical slide of wafer deformation showing where actual slip values are extracted.

4.1.2 Correction of Load Values for Friction

The load-slip traces include a frictional component that also must be compensated for in data analysis. Only limited success has been achieved in attempting to compensate for this effect in the analysis. Initial tests quantify the amount of load resulting from friction. Tests involved mounting the wood wafers in the system but without the inclusion of a pin. Loading the wafer therefore
provided an indication of frictional drag and it's variability both between and within runs.

Microscopic contact area and resultant frictional coefficients are likely to vary with orientation of the wood structure relative to the wafer surface. Runs were therefore completed using wafers sliced in both radial and tangential orientation of growth rings. A typical friction trace is shown in Figure 4.2 below.

![Figure 4.2 A typical friction load-slip curve for wafers between glass plates.](image)

It was anticipated that an average of these replications would yield frictional coefficient data which could be used to derive corrected load values. Subsequent
comparison of data suggested, however, that the presence of the profiled pin used in actual tests effected the magnitude and distribution of compressive forces transferred from the glass plates to the wood wafers.

A less elaborate method was therefore used. On many of the load-slip traces, for runs where pins were included, a discontinuity was observed during the initial stages of loading such a point is marked on Figure 4.3. The discontinuity appeared to occur when friction between the wood and glass was overcome and sliding could commence.

Figure 4.3 A typical load-slip curve from a standard wafer test with pin included.

This load (assumed constant throughout each test) was
subtracted from the entire load slip curve to derive the corrected load values.

4.1.3 The Corrected Load-Slip Curves

Using the corrected slip and load values together with the original load-slip trace, a selection of "corrected" load-slip curves have been constructed. Figure 4.4 shows a typical "corrected" curve. In addition, Figure 4.5 shows corrected load slip curves for various end distances. These curves and associated slides will be discussed in Chapter V.
Figure 4.4  A load-slip curve corrected for frictional load and distortion of the testing apparatus. (Circles are points at which slides were taken.)
Figure 4.5 Replications of corrected load slip curves for three end distances.
4.2 Reduction of Data From the X-ray Technique

Much information is projected onto the x-ray films during scanning. What follows is a description of how this information has been retrieved and how the process may be improved in future work. This is followed by a discussion of how an average curve for bolt bending is derived from original sets of x-ray pictures for more than one replication.

4.2.1 Data Retrieval From X-ray Scans

After developing, each x-ray scan was projected onto a horizontal screen using a photographic enlarger. Measurements taken off the resultant images on the white
screen enabled the progressive change in bolt profiles to be ascertained. A zero or reference line was established for each set of x-ray scans before measurements of the bolt profiles were taken. It was assumed that the central member and its reference pins remained stationary during loading and that the side members and bolt moved with respect to the main member. Six measurements were taken from each x-ray; the first being the distance from the zero line to the reference pin of the side member. The other 5 measurements were taken along the length of the bolt from the outside edge of the joint to the center of the joint. The 5 measurement positions are shown in Figure 4.6 below.

Figure 4.6 Locations of the five displacement measurements taken along the length of the bolt.
For the present study it has been assumed that the joint and the bolt deformation is symmetrical about its central plane (passing through the middle of the length of the bolt). Such an assumption does not account for the possibility of differing behavior resulting from bolt head and nut characteristics. Future work may therefore include extracting bolt profiles along the entire width of the joint. The assumption of symmetry does however appear justified at this stage of the work. Natural variability within wood material and its effect on joint behavior appears to mask the above factors.

A sample of resultant data is shown in Table 4.1 below. The measurements in columns labeled "measured" are taken from the enlarged image of the x-rays. The columns labeled "actual" are the "measured" columns converted into actual displacement of the bolt using the following relationship:

\[
\frac{\text{(x-ray image measurement) (zero line)}}{\text{(Enlargement factor - 5)}} = \text{displacement}
\]

Tables, such as Table 4.1, have been formed for each replication of joints tested. This data is included in the Appendix. A family of averaged profiles of the bolts as loading progresses have been constructed. How these curves are derived is discussed below.
Table 4.1 A sample of resultant data extracted from x-ray image. The columns marked "apparent" are measurements taken from the enlarged x-ray image. The columns marked "actual" are the "apparent" columns converted to actual displacements.

<table>
<thead>
<tr>
<th>POSITION - splice plate (cm)</th>
<th>X-RAY #</th>
<th>1 (cm)</th>
<th>2 (cm)</th>
<th>3 (cm)</th>
<th>4 (cm)</th>
<th>5 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>157.5 .08</td>
<td>33 .06</td>
<td>33 .06</td>
<td>31.5 .03</td>
<td>31 .02</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>159 .11</td>
<td>37 .14</td>
<td>34.5 .09</td>
<td>33 .06</td>
<td>31 .02</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>162 .17</td>
<td>40.5 .21</td>
<td>37 .14</td>
<td>34 .08</td>
<td>31.5 .03</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>168 .29</td>
<td>47 .34</td>
<td>41.5 .23</td>
<td>37 .14</td>
<td>32 .04</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>176 .45</td>
<td>54.5 .49</td>
<td>47 .34</td>
<td>39.5 .19</td>
<td>32.5 .05</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>185 .63</td>
<td>63.5 .71</td>
<td>54.5 .49</td>
<td>43.5 .27</td>
<td>33 .06</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>193.5 .80</td>
<td>75 .90</td>
<td>60.5 .61</td>
<td>47 .34</td>
<td>33.5 .07</td>
</tr>
</tbody>
</table>
4.2.2 Construction of a Bolt Curvature Profiles

Scatter plots of total slip (movement between side and main member) versus localized bolt displacement are constructed for each of the 5 positions along the length of the bolt (Figure 4.7). A line of best fit is then drawn by hand through these scatter diagrams. The five derived graphs have been combined on one axis as Figure 4.8 below. From these intermediate curves, averaged bolt bending curves for various total joint slips may be derived. Using Figure 4.8, vertical lines are drawn at selected total slip values of the joint. The points at which these lines intersect the curves provides paired values for bolt deflection and position along the bolt. A graph of "position along the bolt" versus "bolt displacement" may then be constructed. This is a graphical representation of bolt curvature for a given total slip. Such a family of averaged bolt profiles is shown below in Figure 4.9.
Figure 4.7 Scatter plots of localized bolt displacements at various positions along the bolt. (See figure 4.6 for position location along bolt.)
Figure 4.8 Average curves of localized slip versus total slip for various positions along the length of the bolt. (derived from Figure 4.7.)
4.2.3 Averaging of Whole-Joint Load-Slip Curves

Load slip curves were derived from the testing of complete joints. Such a load-slip curve is shown in Figure 4.10 below. The main objective of this part of the work was, however, the acquisition of bolt bending data. For this reason, load application was not controlled in a sophisticated way and the stepwise loading method used resulted in irregular curves. They do, however, provide an indication of whole joint performance. Each peak
Figure 4.10 Typical load-slip curve from x-ray technique. Roughness is due to loading apparatus.

corresponds to periods of stepwise loading when the two loading screws were turned. Time was allowed prior to each x-ray scan to allow relaxation to decay sufficiently to avoid significant changes in bolt profile from occurring during scanning itself.

An indication of relative joint strength and stiffness may be obtained from these load-slip curves. A family of curves for a single joint type may be graphically averaged using methods similar to those used for the bolt bending curves discussed above.

Firstly, the load-slip curves were smoothed out. A
smooth curve was drawn through the points where the x-ray scans were taken. A series of ten points were taken from each smoothed out load-slip curve at designated slip values. Five load-slip curves of the standard joint configuration were averaged to derive Figure 4.11 below.

Figure 4.11 An averaged load-slip curve for the standard joint configuration.
The amount of joint elongation before catastrophic failure was quite variable. The range for the standard joint configuration was 5 mm to 13 mm. For all joint configurations tested the range was from 3 mm to 20 mm.

4.3 Integration of the Techniques to Determine Load Distribution

The load distribution along the length of the bolt may be modeled by integrating the two techniques. This is done using the bolt profiles in figure 4.9 and an average corrected load-slip curve from the wood laminar technique. The bolted joint is numerically divided into thin increments which correspond to the orientation of wafer in the wood laminar technique. The load supported over the width of each increment may be approximated from the load-slip data for wood wafers. For demonstration purposes the load distribution will be modeled for a standard joint which has sustained a total slip of 4 mm. This corresponds to a load in the order of 20,000 to 25,000 newtons (based on whole joint tests).

The laminar load-slip curve used in this demonstration has been derived from figure 4.5 (7 diameter end distance) which is an average for three wafers in the standard configuration. For simplicity and because levels of
replication are not high, the load-slip curve employed has been simplified considerably.

![Graph of load-slip curve](image)

**Figure 4.12** Idealized load-slip curve from the wood laminar technique.

The localized values for displacement of the bolt within the main and side members has been derived from the bolt profile curve from figure 4.9. The bolt displacement into the main member has been assumed to be equal to the bolt profile curve. Clearance between bolt and holes prior to loading is assumed zero. Penetration of the bolt into the side members is obtained in this process by accounting for the total slip of the joint (4 mm in this case). Penetration of the bolt into wood material along its length is represented below as figure 4.13.
Figure 4.13 Actual displacement of bolt into wood material with model integration increments included.

Displacements in figure 4.13 are converted into equivalent localized loads per unit length of bolt using the average wafer load-slip curve of figure 4.12. The resultant model load distribution is shown in figure 4.14 below.
There have been some assumptions made in this analysis that may contribute to inaccuracies in the load distribution curve above. The first is that it has been assumed that the wafer behaves as if it were of a continuum of wood. The second is the idealized load-slip curve in which the variability of wood is not accounted for. The assumption of constant load during plastic deformation adds to the inaccuracies because wood is unpredictable during plastic deformation. Third, the friction in the shear planes has been ignored here. As a joint is loaded the frictional forces increase carrying an increased amount of load. However this analysis does provide a close approximation of the load distribution along the length of the bolt.
CHAPTER V - DISCUSSION OF TECHNIQUES AND RESULTS

5.0 Introduction

This thesis has mainly been directed towards development of two new techniques rather than the collection and complete analysis of large quantities of data. Discussion will largely be limited to the behavior of the standard joint configuration (figure 1.1) and the effects of changing some selected variables.

Data from the two techniques may be combined to enable inferences to be made about the whole joint system. Information is produced in the following forms:

- time-lapse colored photographs from wood laminar technique
- load-slip traces from the wood laminar technique
- x-ray scans of bolted joints
- load-slip traces from the x-ray technique
- failed test specimens from both techniques

5.1 Behavior of the "Standard Joint" Configuration

The arrangement adopted as a standard in this investigation is the three member, double shear joint shown in figure 1.1. The behavior of the joint will first be discussed in terms of the wood laminar technique and then the x-ray scanning method.
5.1.1 Observations from the Wood Laminar Technique

This approach is being used as a tool to directly infer the behavior of wood within the joint during loading. Here, the deformation of wood around a bolt will first be considered for a radial section of wood then for a tangential section. Intermediate angles may be investigated in studies to follow.

Figure 5.1 is a photograph of the first in a series of slides from a typical test run on radially cut material (the bolt axis runs in the tangential direction). The load on the test specimen in this photo is zero. Figure 5.2 shows the typical corrected load-slip trace obtained in chapter 4. The points marked along the curve correspond to...
Figure 5.2 A typical corrected load-slip trace from the wood laminar technique. Points marked "a" to "f" correspond to photos in figure 5.3a to 5.3f.
photographs that were taken as loading progressed. These are found in figures 5.3a to 5.3g and are typical for loading to catastrophic failure of the wafer.

Figure 5.3 Photographs for a typical test run on a radial wafer.
Figure 5.3 continued
A number of modes of deformation are evident in wood material around the bolt. The main zones and types of force are represented diagrammatically in figure 5.4 below. Each of these zones and their interaction will be considered in turn.

Figure 5.4 A schematic showing general zones of deformation around the bolt.
The clearance above the pin seen in figure 5.1 is closed up in the next photograph (figure 5.3a) and the gap below the pin has enlarged slightly. This occurs as the load applied to the wood wafer exceeds frictional restraint and the wafer begins to slide. The gap below the pin does not, however, appear to enlarge further (figure 5.3a to figure 5.3b), until figures 5.3c to figure 5.3g, are reached when a large amount of wood deformation occurs. Figures 5.3a to 5.3c do not show signs of macroscopic failure. There may, however be deformation of wood fibers at this stage since figure 5.3c lies within the highly non-linear section of the load-slip curve. Figure 5.3d shows some compression failure above the pin. This is manifested as slight darkening of earlywood material and the onset of displacement of longitudinal wood components around the bolt. At this stage the load-slip curve has somewhat leveled off as the wood deforms plastically around and above the pin. As loading is continued, figure 5.3e shows considerably more compression failure along with some longitudinal internal splitting. The compression failure is occurring in directions both parallel and perpendicular to the direction of loading (longitudinal and tangential directions).

Figures 5.3f and 5.3g show continued compression failure and longitudinal shear of the specimen until total failure in tension perpendicular occurs in figure 5.3g.
The steel pin and the section of wood that has failed in compression acts as a wedge forcing the split to propagate longitudinally in the specimen. This splitting of the wood material may better be seen in figure 5.5, an overall view of the failed test specimen.

Figure 5.5 Overall view of failed radial test specimen

The deformation of wood material around the bolt is somewhat different in the tangential section. The thickness of the wood wafer is about one forth the thickness of the growth ring. Therefore the pin can be located in either earlywood or latewood. Figure 5.6 shows a series of photographs from a typical test run using tangentially cut
Figure 5.6 Photographs for a typical test run using a tangentially cut wafer.
Figure 5.6 continued
wafers. Figure 5.6c shows the onset of darkening around the loaded side of the pin. This darkening is caused by compression failure of the wood. Future work will consider the causes of this change in opacity in terms of wood anatomy.

As loading progresses two types of compression failure become apparent in directions perpendicular and parallel to the grain (figures 5.6d to 5.6h). Firstly a column of compression failure perpendicular to the grain forms above the pin. This becomes rather tall (in the order of one bolt diameter) before catastrophic failure of the joint occurs (figures 5.6h and 5.6i). Causes of the ribbing effect in the column of compression failure is not well understood. Again, future work will be carried out on this phenomenon. The transition area between parallel and perpendicular compression failure is marked by a shear failure or crack that runs the length of the column of compression failure. There is also some tension failure parallel to the grain at the area that the compression failure perpendicular to the grain begins. These areas of compression failure resemble the behavior noted for radial tests (figure 5.4). However the compression column is more pronounced in the tangential sections and there is a greater amount of slip before the specimen fails.

In figure 5.6i and j, shear failure occurs and splitting apart of the specimen follows immediately. This splitting of the wood is caused by the shear forces above
the pin and by tension forces perpendicular to the grain that are induced by the pin and compressed wood. This effect may be seen in both the radially and tangentially oriented tests. If square bolts were used then it is likely that the compression failure perpendicular to the grain would be maximized and the parallel compression failure would be minimized. This would be desirable because wood is stronger in compression perpendicular than parallel to the grain. The preliminary tests carried out here using pins with a flat ground on them depend on this principle.

The above results suggest that the ultimate strength of bolted joint is dependent not only on the compression strength of the wood parallel to the grain, but also on its compression strength perpendicular to the grain. Reduction in the latter would appear to reduce tension perpendicular forces and thus increase joint performance.

Comparison of Failure From Two Techniques:

The characteristic compression failure found in the wood laminar technique was also observed in the completed joints tested. Figure 5.7 is a photograph of the failures exposed when main members are machine planed.
5.1.2 Behavior of Complete Joints: X-ray Scanning

Introduction:

The x-ray technique has been developed to provide information on the behavior of the system in the third and mutually perpendicular plane. The standard joint will be discussed first. This will be followed by considering the use of metal splice plates, the effects of different plate thicknesses and changes in the L/D ratio.

The center line (axial) profiles of the bolts shown in figure 4.9 were numerically developed in chapter 4. These represent the variation in the amount of displacement along the length of the bolt as loading of the joint progresses.
Bolt displacement is here defined as the amount the bolt has moved from its original position. This assumes the main member has remained stationary. It is also assumed that bolt clearance is zero and therefore bolt displacement directly implies wood deformation. Correction for the effect of clearance between bolt and hole could be accounted for in future work. This may be necessary if joint with larger clearance values are modeled.

Standard joint behavior:

Integration of bolt bending and wafer load-slip data has enabled load distribution curves to be developed in chapter 4. Figure 5.8 below demonstrates a typical intermediate curve in which the total joint slip was 4 mm. The greatest amount of bolt displacement (wood deformation) occurs at the outside edge of the wood splice plate. These displacements from the initial (no load) position are greater than the total slips of the joint. At approximately one forth of the way into the wood splice plate, the bolt displacement equals the total slip of the joint. The splice plates exert bending moments on the bolt which tends to pivot about this point. The position of this neutral plane within the side plates may, however, move during loading of the joint. Further testing and analysis is needed to fully explore these effects.
Figure 5.8 The constructed load distribution curve along a bolt in a 3 member, double shear joint. When joint slip is 4mm under an approximate load of 25,000 newtons.

Load distribution in main member and its improvement:

As may be expected maximum wood deformation in the main member occurs adjacent to the shear plane. Material displacement at the center of the main member may remain zero or even possibly attain negative values at certain stages of joint loading. This ineffectiveness of load transfer at the center of the joint becomes more evident as L/D ratios increase. More efficient joint design may therefore be achieved by using small L/D ratios (less than 6) or a third metal splice plate inserted into the center of the main member.

The National Design Specifications (1982) may be used to obtain an indication of the effectiveness of such a modification. Figure 5.9 below represents two similar joints (metal plates, 1 inch bolt into 9.5 inch wide
Douglas-fir main member) except for the addition of a plate recessed into the center of the main member.

Standard Joint:
Design load = 10,412 pounds

Modified Joint:
Design load = 15,303 pounds

Figure 5.9  Joints of conventional and modified design
This modification, though rather costly, would reduce the effective L/D ratio and lead to more uniform load transfer from main to side members. An increase of 46% has been achieved in the above example. The effectiveness of the modification may be expected to increase with increasing L/D ratio.

The effect of using metal side plates:

The use of metal splice plates has been found to significantly affect bolt bending behavior. Joints with plates of 20 gauge, 1/4 inch, and 1/2 inch in thickness were tested. With the thicker metal splice plates (1/4 and 1/2 inch) the negative central displacement discussed above was followed by load reversal and compressive wood failure as joint loading reached high levels. This transition did not occur, however, until considerable bending of the bolt had taken place. For the wood and thin metal splice plates (20 gauge) the joints reached catastrophic failure before this negative displacement area could close up and compressive deformation could commence at the center of the main member.

Surveying the x-ray scans indicates that less bolt bending occurs when 1/4 and 1/2 inch metal splice plates are used. Results from tests using thin metal splice plates (20 gauge) suggest an amount of bolt bending similar to that occurring when wood splice plates are used. The thicker metal splice plates appear to restrict the ends of
the bolts and limit the amount of bending. This effect is known as bolt end fixity. With the wood splice plates, a less rigid foundation was provided for the bolt head. The bolt ends were in this way less effectively restrained from yielding to the bending moments applied. The bolt head and nut may also significantly distort the thin metal splice plates. The thicker metal plates did, however, provide a rigid foundation. In this way, metal plates of sufficient thickness tend to reduce the amount of bolt bending and create a more even distribution of load along the length of the bolt. This restraint is, however, of limited significance, particularly as the length to diameter (L/D) ratios are increased.

In all the joints tested with wood splice plates the ultimate failure occurred in the wood splice plate. When metal splice plates were used the catastrophic or limiting failure occurred when the end of the main member failed in longitudinal shear.

5.2 The Effects of Selected Variables on Joint Behavior

Much data has been collected in this study, largely in the process of developing the techniques. Selected variables have been varied with a view to developing preliminary sensitivity relationships. Each of these will be considered briefly in turn.
5.2.1 End-Distance

The distance from the bolt center to the end of the members significantly affects the nature of failure and performance of bolted joints. The National Design Specifications (1982) require a minimum end distance of 7 bolt diameters. In the wood laminar technique a number of end distances were tested. Joints constructed with end distances of 5 diameters and greater had no apparent difference in ultimate strength. However, the end distance of 5 diameters had a tendency to shear out at an earlier displacement than end distances of 7, 9, and 11 diameters. An end distance of 3 diameters caused an early shear failure in the test specimen with no detectable macroscopic compression damage of the wood material. Replication was not sufficient to enable reliable numerical conclusions to be drawn. The techniques could however usefully be used to investigate these relationships in future work. The end distance effect was not considered in the x-ray work.

5.2.2 Bolt diameter and L/D ratio

L/D ratio is the length of the bolt in the main member over the diameter of the bolt. A limited number of tests were carried out using larger L/D ratios than the standard (6). Bolts of 1/4 and 3/8 inch diameters were used to give L/D ratios of 12 and 8 respectively. Examples x-ray scans for these larger L/D ratios are shown as figure 5.10 below. There appeared to be little bending in the central
section of the bolt and more bending towards the interface between side and main members. Loading of the joint produces axial tensile forces in the bolt. This draws the joint members together, thus increasing the frictional forces at the shear planes and thereby increasing the load carrying capacity.

![Comparison of bending characteristics of bolts with L/D ratios of 6, 8, and 12.](image)

**Figure 5.10** Comparison of bending characteristics of bolts with L/D ratios of 6, 8, and 12.

5.2.3 Grain Orientation

In the wood laminar technique, both radial and
tangential sections were tested. The results from using radial sections appeared to be more consistent. The results of the tangential sections depended upon the location of the bolt hole being in latewood or earlywood. When bolts are used to connect laminated beams, it is more likely that their axis would be orientated parallel to the growth ring (radial section tests). In solid wood members the orientation could be in any direction. It is recommended that radial sections be used in future work since laminated beams are predominantly used in large structural systems.

5.2.4 Flatted Bolts

When observing wood deformation in standard runs, a column of compression failure developed above the pin (See figure 5.3). The development of this mode of deformation appeared to enhance joint performance at large slip values. In an effort to encourage the formation of this type of compression failure parallel to the grain, a flat was therefore ground on the pin. This modification did increase the width of the zone of compression failure but did not appear to significantly increase ultimate strength (See figure 5.11a to d below).
Figure 5.11 A series of photographs of test done with a flatted pin.
5.2.5 Natural Defect in the area of the Bolt Hole

A limited number of wood laminar tests were carried out to explore the effect of natural defects on modes of failure. In this case the bolt hole in the wood wafer was placed near a knot to observe qualitatively the effects on failure. This method provided a means to investigate the effect of wood quality on many aspects of joint performance. Present design specifications make few adjustments for wood quality. An example set of photographs is included below in figure 5.12 to demonstrate the potential usefulness of the method.

5.2.6 Multiple Bolt Simulation

The wood laminar technique could provide a useful means of investigating factors which influence the performance of various multiple bolt configurations. The use of a conventional single row of bolts can take up considerable space at the ends of a structural member. This is especially true if great strength is required. Arrangements other than the linear alignment of bolts presently adopted could make more efficient use of space and material.

Three multiple bolt configurations were tested here. Photographs of failed wafers incorporating these configurations are shown as figure 5.13. These were preliminary tests carried out to demonstrate the application of the technique. Replication was insufficient
Figure 5.12 Series of photographs of a wafer with knot included.
Figure 5.13 Failed wafers from the multiple bolt configurations tested.
to derive reliable conclusions about their relative performances. In all the tests carried out on multiple bolt configurations, displacements were small and little compression damage occurred prior to catastrophic failure in shear. This may have been due to the small clearances between the pin and pin hole, and the accuracy in the alignment of the system. Evidently, in service situations, clearances and hole alignment vary considerably and load sharing is unlikely to be as effective. In addition to investigating more configurations, an important application of the technique could therefore be to investigate the importance of fabrication accuracy. This would particularly pertain to hole clearances and the accuracy of hole positioning in multiple bolt systems. This technique could also be used to investigate bending moments on multiple bolted joints. The addition of a side load to accomplish this appears feasible. Presently, design specifications do not account for bending moments on bolted wood joints although it is highly likely that even a small moment could severely reduce joint performance in tension.
CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

6.0 Introduction

This thesis has been concerned with the development of techniques which will enable a better understanding of bolted wood joint behavior to be gained. They were developed to provide both qualitative and quantitative information. An underlying objective has been to establish approaches which may enable rigorous rather than trial and error approaches to design to be developed.

6.1 Conclusions

The wood laminar technique provides a two dimensional representation of a bolted joint. It is designed to enable wood deformation around the bolt to be viewed and to investigate how it is effected by certain joint variables. The X-ray technique was designed to quantify material behavior in the third dimension of the bolted joint. This technique is used to study the bending characteristics of bolts inside a joint. Conclusions about the wood laminar technique followed by the X-ray technique are stated below. This is followed by suggestions on further research and applications of the two techniques.

6.1.1 Wood Laminar Technique

A. The failure of wood around a bolt has been found to be a combination of compression failure both parallel
and perpendicular to the grain. The bolt acting like a wedge induces tension forces perpendicular to the grain of the wood. Thus the ultimate strength of a bolted joint is influenced not only by the compressive strength parallel to the grain but also by compressive strength and tensile strength perpendicular to the grain.

B. The use of this method shows potential in studying the effects of wood quality on bolted joint strength.

C. The design of multiple bolted joints is presently based primarily on extrapolation of data from single bolt tests. The approaches discussed here in have potential for multiple bolt simulation and optimization. Variables include bolt spacing as well as a range of new geometries. The technique may be used to carry out sensitivity studies of selected joint variables to aid with optimization of joint design.

D. The wafer technique has shown that the shape of the bolt has an influence on the mechanism of wood failure that occur around the bolt. Further evaluation of bolt sections in considered justified.

E. Orientation of the wood structure has an effect on the nature of deformation around the bolt. Tangentially cut wafers (bolt axis in radial direction) tend to display a larger area of compression failure perpendicular to the grain than due the radially cut sections. Information of this nature could prove useful when specifying preferred
orientations for design specifications.

6.1.2 X-ray Technique

The x-ray technique was developed to indicate the effects that joint configuration and materials have on the distortion of the system. In particular the bolt bending characteristics inside joints as they are loaded to failure. The advantage is that it implies behavior while testing whole joints as opposed to the wood laminar technique which is an indirect method.

As with the wafer method, there are two underlying uses for the technique. Firstly, specific inferences about joint behavior may be made by considering x-ray results alone (see section 5.1.2). Secondly, and possibly of farther reaching importance, the two methods when combined could enable numerical models to be developed (see section 6.1.3 below). Two of the more obvious and immediate conclusions from tests in this thesis are the following:

A. The bolt bending characteristics inside a bolted wood joint are influenced by the thickness and material of the side members. Sufficiently thick metal side plates will reduce the amount of bolt bending and thus produce a more even distribution of load along the length of the bolt.

B. The slenderness of the bolt (the L/D ratio) effects bending characteristics. The larger the L/D ratio the more concentrated the loads are near the shear planes of the joint.
6.1.3 Combining the Techniques

As implied above, numerical methods based on a combination of the two methods has potential for aiding in joint design. The development of a three dimensional computer model could enable a wide range of systems to be explored. Only the most promising one would then be fabricated for testing. The integration of the techniques here (in this thesis) has been done to a limited extent as pointed out below.

- The load distribution along the length of the bolt may be determined by integrating the bolt bending curve and the load slip curves from the wood laminar technique.

6.2 Recommendations for Future Research Using These Techniques

A. Development of a computer model used to investigate changes in wide ranges of variables. This model would be based on basic data derived from the techniques developed here.

B. One of the most useful application of the wood laminar technique is the simulation of multiple bolt configurations. Research is needed in this area since the design of these joints are based primarily on extrapolation of data from single bolt tests.

C. Investigation of the effect of bending moments on bolted joints is needed. The wood laminar technique may be
adapted simulate bending moments by adding a side load to the wafer.

D. Testing of large diameter bolted joints is needed. The majority of testing to date has been on small diameter bolts (less than one inch). The wood laminar technique would reduce the need for full size testing of large diameter bolted joints.

E. Study the effects of bolt hole to bolt diameter ratio (bolt clearance) and how this effects wood failure around the bolt.

F. The accuracy of joint fabrication and its effect on load sharing.

G. Determine optimum bolt spacing to reduce the size of joints and increase their efficiency.

The two techniques are considered to have potential in gaining an insight to the behavior of bolted joints in an aim at optimizing their design.
BIBLIOGRAPHY


Lantos, G. 1969. Load Distribution in a Row of Fasteners Subject to Lateral Load. Wood Science 1(3):129-136(Jan.).


APPENDIX

Tables used to construct bolt profile graphs in figure 4.9 and are similar to table 4.1. A total of 36 such tables were created for the other whole joints that were tested.

Table A.1 Replication 1

<table>
<thead>
<tr>
<th>POSITION (cm)</th>
<th>splice plate (cm)</th>
<th>5 (cm)</th>
<th>4 (cm)</th>
<th>3 (cm)</th>
<th>2 (cm)</th>
<th>1 (cm)</th>
<th>LOAD (kg force)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>155.5</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>157.03</td>
<td>31</td>
<td>30</td>
<td>30</td>
<td>30.5</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>2</td>
<td>159.07</td>
<td>35</td>
<td>33</td>
<td>31</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>162.12</td>
<td>37</td>
<td>4.5</td>
<td>32</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>4</td>
<td>167.2</td>
<td>35</td>
<td>40</td>
<td>36</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>171.43</td>
<td>56</td>
<td>48</td>
<td>40</td>
<td>33</td>
<td>33</td>
<td>33.06</td>
</tr>
<tr>
<td>6</td>
<td>187.55</td>
<td>68.5</td>
<td>56</td>
<td>44</td>
<td>33.5</td>
<td>27</td>
<td>27.06</td>
</tr>
</tbody>
</table>

Table A.2 Replication 2

<table>
<thead>
<tr>
<th>POSITION (cm)</th>
<th>splice plate (cm)</th>
<th>5 (cm)</th>
<th>4 (cm)</th>
<th>3 (cm)</th>
<th>2 (cm)</th>
<th>1 (cm)</th>
<th>LOAD (kg force)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>153.0</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>157.5</td>
<td>33</td>
<td>33</td>
<td>31.5</td>
<td>31</td>
<td>31</td>
<td>31.02</td>
</tr>
<tr>
<td>2</td>
<td>159.11</td>
<td>37</td>
<td>34.5</td>
<td>33</td>
<td>32</td>
<td>32</td>
<td>32.02</td>
</tr>
<tr>
<td>3</td>
<td>162.17</td>
<td>40.5</td>
<td>37</td>
<td>34</td>
<td>34.5</td>
<td>34.5</td>
<td>34.5</td>
</tr>
<tr>
<td>4</td>
<td>168.29</td>
<td>47</td>
<td>41.5</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37.04</td>
</tr>
<tr>
<td>5</td>
<td>174.45</td>
<td>54.5</td>
<td>47</td>
<td>39.5</td>
<td>39.5</td>
<td>39.5</td>
<td>39.5</td>
</tr>
<tr>
<td>6</td>
<td>185.63</td>
<td>63.5</td>
<td>54.5</td>
<td>43.5</td>
<td>43.5</td>
<td>43.5</td>
<td>43.5</td>
</tr>
<tr>
<td>7</td>
<td>193.8</td>
<td>75</td>
<td>60.5</td>
<td>47</td>
<td>33.5</td>
<td>33.5</td>
<td>33.5</td>
</tr>
</tbody>
</table>
### Table A.3  Replication 3

<table>
<thead>
<tr>
<th>POSITION</th>
<th>splice plate (cm)</th>
<th>5 (cm)</th>
<th>4 (cm)</th>
<th>3 (cm)</th>
<th>2 (cm)</th>
<th>1 (cm)</th>
<th>LOAD (kg force)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
</tr>
<tr>
<td>0</td>
<td>154.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>1</td>
<td>156.5</td>
<td>0.05</td>
<td>36.5</td>
<td>0.13</td>
<td>34.0</td>
<td>0.08</td>
<td>32.0</td>
</tr>
<tr>
<td>2</td>
<td>157.5</td>
<td>0.07</td>
<td>38.1</td>
<td>0.16</td>
<td>36.1</td>
<td>0.12</td>
<td>33.0</td>
</tr>
<tr>
<td>3</td>
<td>161.0</td>
<td>0.14</td>
<td>41.5</td>
<td>0.23</td>
<td>38.0</td>
<td>0.16</td>
<td>34.0</td>
</tr>
<tr>
<td>4</td>
<td>168.0</td>
<td>0.28</td>
<td>48.3</td>
<td>0.36</td>
<td>43.2</td>
<td>0.26</td>
<td>36.5</td>
</tr>
<tr>
<td>5</td>
<td>177.0</td>
<td>0.46</td>
<td>61.6</td>
<td>0.62</td>
<td>50.5</td>
<td>0.41</td>
<td>40.5</td>
</tr>
</tbody>
</table>

### Table A.4  Replication 4

<table>
<thead>
<tr>
<th>POSITION</th>
<th>splice plate (cm)</th>
<th>5 (cm)</th>
<th>4 (cm)</th>
<th>3 (cm)</th>
<th>2 (cm)</th>
<th>1 (cm)</th>
<th>LOAD (kg force)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
</tr>
<tr>
<td>0</td>
<td>-20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>1</td>
<td>-13.5</td>
<td>0.15</td>
<td>29.1</td>
<td>0.18</td>
<td>26.5</td>
<td>0.13</td>
<td>24.0</td>
</tr>
<tr>
<td>2</td>
<td>-6.0</td>
<td>0.30</td>
<td>38.2</td>
<td>0.36</td>
<td>33.0</td>
<td>0.26</td>
<td>28.0</td>
</tr>
<tr>
<td>3</td>
<td>-4.0</td>
<td>0.38</td>
<td>43.4</td>
<td>0.46</td>
<td>37.3</td>
<td>0.34</td>
<td>29.5</td>
</tr>
<tr>
<td>4</td>
<td>6.0</td>
<td>0.54</td>
<td>52.6</td>
<td>0.64</td>
<td>42.5</td>
<td>0.45</td>
<td>33.0</td>
</tr>
<tr>
<td>5</td>
<td>10.0</td>
<td>0.62</td>
<td>56.7</td>
<td>0.72</td>
<td>45.0</td>
<td>0.50</td>
<td>35.0</td>
</tr>
<tr>
<td>6</td>
<td>22.0</td>
<td>0.86</td>
<td>68.5</td>
<td>0.97</td>
<td>54.5</td>
<td>0.69</td>
<td>40.0</td>
</tr>
</tbody>
</table>

### Table A.5  Replication 5

<table>
<thead>
<tr>
<th>POSITION</th>
<th>splice plate (cm)</th>
<th>5 (cm)</th>
<th>4 (cm)</th>
<th>3 (cm)</th>
<th>2 (cm)</th>
<th>1 (cm)</th>
<th>LOAD (kg force)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
<td>act.</td>
<td>apar.</td>
</tr>
<tr>
<td>0</td>
<td>154.5</td>
<td>0</td>
<td>30.0</td>
<td>0</td>
<td>30.0</td>
<td>0</td>
<td>30.0</td>
</tr>
<tr>
<td>1</td>
<td>156.0</td>
<td>0.03</td>
<td>35.0</td>
<td>0.10</td>
<td>32.5</td>
<td>0.05</td>
<td>30.0</td>
</tr>
<tr>
<td>2</td>
<td>158.5</td>
<td>0.08</td>
<td>37.0</td>
<td>0.14</td>
<td>34.0</td>
<td>0.08</td>
<td>32.0</td>
</tr>
<tr>
<td>3</td>
<td>161.0</td>
<td>0.13</td>
<td>38.5</td>
<td>0.17</td>
<td>36.0</td>
<td>0.12</td>
<td>33.0</td>
</tr>
<tr>
<td>4</td>
<td>165.0</td>
<td>0.21</td>
<td>46.0</td>
<td>0.32</td>
<td>40.5</td>
<td>0.21</td>
<td>35.0</td>
</tr>
<tr>
<td>5</td>
<td>172.5</td>
<td>0.36</td>
<td>53.0</td>
<td>0.46</td>
<td>45.0</td>
<td>0.30</td>
<td>37.5</td>
</tr>
<tr>
<td>6</td>
<td>181.0</td>
<td>0.53</td>
<td>63.0</td>
<td>0.66</td>
<td>52.5</td>
<td>0.45</td>
<td>41.5</td>
</tr>
<tr>
<td>7</td>
<td>189.5</td>
<td>0.70</td>
<td>73.5</td>
<td>0.87</td>
<td>59.5</td>
<td>0.59</td>
<td>47.0</td>
</tr>
</tbody>
</table>