Bolted Connection Research: Present and Future

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Abstract

In 1991, the design practice for bolted connections in the United States was changed from an empirical basis to the yield theory a design practice that is used in many other countries. It has been determined that the yield theory adequately describes single-bolt connections. However, because multiple-bolt connections are not as well understood, current design practices would benefit from additional research. This paper identifies some specific research needs.

Introduction

In the 1991 *National Design Specification® for Wood Construction (NDS®)* (AF&PA, 1991), design values for the lateral strength of a single-bolt connection are based on the yield theory developed by Johansen (1949). The strength of a multiple-bolt connection is calculated by summing the values for single-bolts after multiplying those values by a group-action factor developed by Cramer (1968). The strength in both single- and multiple-bolt connections is achieved by sufficient spacing, end distance, and edge distance, as well as proper fabrication tolerances.

This paper will not address the history of bolted-connection research. Soltis and Wilkinson (1987) have presented the state of the art of bolted connections through 1986, and the Forest Products Society (FPS, 1993) has presented the state of the art of connections consisting of all types of fasteners.

Rather, this paper summarizes those areas in which the research community currently has substantial data and knowledge, as well as those areas in which more research is needed.

Single-Bolt Connections

Much of the past experimental and analytical research has focused on single-bolt connections that are loaded parallel to grain in compression. The consensus from the International Workshop on Wood Connectors (FPS, 1993) was that the yield theory adopted by the NDS in 1991 adequately describes single-bolt behavior; this theory is the basis for specifications in most countries. The yield theory has been verified experimentally by a number of researchers (Soltis and Wilkinson, 1987). It also agrees with the empirical approach by Trayer (1932), which was the basis for design prior to the 1991 NDS (AF&PA, 1991).

Most of the experimental verification has used compressive tests that are loaded parallel to grain. This simplification was made because compressive tests are so much easier to conduct than tensile tests, and the single fastener made interpretation straightforward. The limited available data from tests conducted perpendicular to grain exhibits more variability than data from bolt tests conducted parallel to grain. In addition, variability of bolt capacity perpendicular to grain is influenced by bolt diametez Therefore, tests for the perpendicular-to-grain direction require more replications to establish data that offer the same degree of statistical confidence.

Calculation of allowable capacities for bolts using the yield theory requires material-property input for the bending-yield strength of the bolts and the dowel bearing strength of the wood. Most yield strengths of steel are determined by tensile tests; thus, most published values reflect tensile yield strength. In Appendix I of the NDS (AF&PA, 1991), an approximate bolt bending yield strength (F_{yb}) is calculated by averaging the bolt tensile yield and tensile ultimate stresses.

The dowel bearing strength is determined by pressing a dowel shank laterally into a wood specimen. Different countries use various test procedures to establish dowel bearing strength, resulting in somewhat different values. The test method used in North America is not fully standardized, but it has nearly passed the consensus process conducted by the American Society for Testing and Materials (ASTM).

Full-scale, single-bolt connections have been tested using bolts with diameters ranging from ½ to 1½ in. (13 to 38 mm). The yield theory adequately predicts performance over this range of sizes. However, the NDS limits bolt diameter to 1 in. (25.4 mm) due to concerns about fabrication tolerances of connections made with multiple, large-diameter, relatively stiff bolts.

Multiple-Bolt Connections

Multiple-bolt connections are not as well understood as single-bolt connections. More research is needed to support current design practices. Multiple-bolt research is a contemporary focus of the international wood research community but definitive results are several years off.

The allowable capacity of a multiple-bolt, single-row connection is calculated by summing the single-bolt values after multiplying them by appropriate adjustment factors, including a group-action factor, C_g. The group-action factor used in the United States varies considerably from that used in other counties (for example, see the paper by Smith in this issue of *Wood Design Focus).* It is based on research by Cramer (1968) in which verification tests were performed on perfectly fabricated test specimens. The theory developed by Cramer includes the modulus of elasticity of the wood, which is used to determine wood deformations between bolts placed in a row. It is this deformation in the wood that accounts for the unequal distribution of load to each bolt in a line of bolts. The NDS adaptation of Cramer's theory is based on parallel-to-grain, modulus-of-elasticity

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values. Thus, the group-action factor has not been verified for a row of bolts loaded perpendicular to grain. It is not yet known what effects fabrication tolerances have on the group-action factor.

Cramer (1968) provided an elastic theory with experimental verification for small length-to-bolt diameter ratios, which represents a Mode I yield-theory failure. The theory proposed by Cramer does account for bolt bending and has not been verified for large length-to-bolt diameter ratios, or Mode II or III failures. It is speculated that Mode I failure is a worst-case scenario for the group-action factor, but there is still a need for supporting experimental verification.

The group-action factor defined by Equation 7.3-1 in the NDS (AF&PA, 1991) is based on an analytical approach described by Zahn (1991). This approach does not represent new research data, but rather an alternate way to present the theory developed by Lantos (1969).

Most experimental research on multiple-bolt connections was conducted for a maximum of two bolts in a row, where the group-action factor is unity. More experimental verification for other geometries and length-to-bolt diameters is needed. Research data are sparse that support specific designs for more than four bolts in a row

Current practice for determining the allowable capacity of multiple rows of bolts is to sum the rows, multiplying each row separately by the group-action factor (AF&PA, 1991). Some other countries use a row factor in addition to a group-action factor. The row factor is employed as an additional reduction on the strength of the multiple-bolt connection. No research in the Unites States is completed or ongoing to support the use of a row factor.

Various bolt geometries, such as staggered bolt patterns, are treated as either single or multiple rows of bolts in the NDS, depending on the gauge and spacing of the bolts (AF&PA, 1991). This is an engineering judgement, which requires further supporting research.

It is assumed that eccentric loads in connections are avoided by loading the connection through the center of resistance for the bolt group. Limited research by Fantozzi (1988) has shown that bending moments can significantly reduce the tensile strength of a connection. Eccentricity may be induced into a concentrically loaded connection if the fabrication tolerances are such that the load is not equally distributed to the bolts. Research is needed to address this possibility.

More research is also needed on the effects of fabrication tolerances. Wilkinson (1993) investigated oversized and misdrilled holes, which are defined as holes drilled at some angle other than perpendicular to the wood surface. He found reductions in connection strength, but the results were too variable to make specific design recommendations.

Current design criteria for spacing, end distance, and edge distance for bolted connections are based on experimental observation. Most of the research has been performed on connections made of Douglas-fir, with small length-to-bolt diameter ratios (Mode I failures in yield theory), and loaded parallel to grain in compression. For these situations, ample verification exists to verify spacing, end distance, and edge distance requirements. More research needs to be conducted on other species and other loading angles with respect to the grain.

Other Factors Affecting Bolted-Connection Strength

Other factors that influence bolted-connection strength are moisture content, load duration, and preservative or fire-retardant treatments.

Experimental verification exists for the reduction in joint strength due to wet conditions for Mode I failures. This is again a worst-case scenario. Larger length-to-bolt diameter ratios have not been extensively studied. The yield theory suggests that the effects of moisture content may not be as large at the larger length-to-bolt diameter ratios where bolt bending governs, such as the failure Modes II and III.

The effect of load duration on the strength properties of wood has long been recognized. Current design practice assumes that the load-duration factor applies to the stresses on the wood beneath a bolt regardless of length-to-bolt diameter ratio. Intuitively one expects the effect to be greater for Mode I failures (wood crushing) than for Mode III failures (bolt bending). However, additional research is needed to verify this supposition.

Research has not been conducted on the effect of preservative or fire-retardant treatment on single-bolt strength, or on the distribution of load, spacing, end distance, or edge distance. The design engineer should check with the treatment/chemical suppliers to determine if any reduction factors are required.

Summary

The change to the yield theory as the basis for bolted-connection design was welcomed by the engineering community in the United States. The yield theory provides a mechanistic basis for engineering judgement and an equation format. Single-bolt connections have been widely investigated and are well documented. However, current design practice for multiple-bolt connections, especially those that have more than four bolts, would benefit from additional experimental research.

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