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Experimental and numerical analysis of a halved and tabled traditional timber scarf joint

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Abstract

Traditionally constructed heavy timber trusses, found in timber framed buildings and bridges, employ various traditional joints, among them the lower chord scarf joint. This paper examines the behavior of a halved and tabled scarf joint, which was studied as an isolated structural component using experimental tests and finite element analyses. Experimental tests identified two different limit states for these particular scarf joints: shear failure parallel to grain and tension failure perpendicular to grain. The possibility of failure due to tension perpendicular to grain results from variations in grain angle and means that the limit state of shear failure parallel to grain, typically assumed in analysis and design, is unconservative. For the purposes of design and rehabilitation, the authors propose that the scarf joint be treated as a member subject to combined bending and axial tension forces. The results of the finite element analysis, performed using solid continuum elements in ABAQUS, are in good agreement with the experimental test results. In addition to finite element models, the authors use analytical spring models to demonstrate that when developing a two-dimensional model of a truss with lower chord scarf joints, serviceability limit states be checked with a model that reduces the lower chord section properties in the vicinity of the scarf joints.

Keywords: Timber joints; Covered wooden bridges; Heavy timber framing

1. Introduction

The art of traditional wooden joinery used in heavy timber framed buildings and bridges relies on complex cuts in the ends of wooden members to enable their connection without reliance on mechanical fasteners. System analyses performed on the timber trusses used in historic covered bridges have identified the lower chord scarf joints as the most significant contributor to global truss stiffness [14,15]. While scarf joint details in wooden trusses are as varied as the trusses themselves, one of the simplest and most common designs is a halved and tabled scarf joint (Fig. 1). All of the cuts in this specific type are orthogonal, and the table (or notch at the center of the joint) transfers tensile force through wood-on-wood bearing [16]. Determining the behavior of halved and tabled scarf joints for the purpose of bridge rehabilitation was the goal of this research.

Halved and tabled scarf joints were used in Morgan Bridge [15], an 18.29 m (60 ft to 0 in.) long queen post truss, built in 1898 in Belvidere, Vermont. Morgan Bridge was one of 75 covered wooden bridges that were studied between 2002 and 2004 by the National Covered Bridges Recording Project (NCBRP), directed by the Historic American Engineering Record (HAER). The authors performed system-level load tests and developed numerical models to study Morgan Bridge in part for the purpose of determining the suitability of using current engineering tools to properly analyze these unique structures, for the purpose of rehabilitation. The lower chord of Morgan

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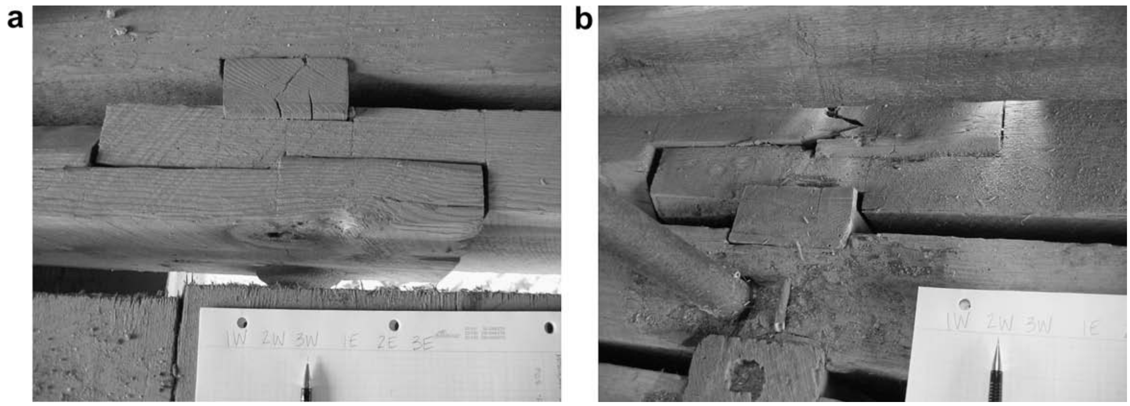

Fig. 1. Examples of halved and tabled scarf joints on Morgan Bridge.

Bridge uses three halved and tabled scarf joints staggered along the length of each truss [15]. The condition of the joints on the bridge varies between very good and very poor condition (Fig. 1). Fig. 1b exemplifies a scarf joint in poor condition, with a full-depth crack that initiated in the shear plane near the corner of the notch, but ultimately failed through some combination of shear and tension stresses.

Recognizing the impact of scarf joints on global truss stiffness, four joints were replicated from Morgan Bridge and tested experimentally in tension to isolate their individual structural behavior from truss system behavior. Additionally, full three-dimensional finite element models with contact were developed using ABAQUS software [9] and compared with the experimental results. Previous authors have performed similar studies on traditional [7,8,13,12] as well as modern [10,11] timber joints. The results of this work, including details of scarf joint behavior and tools to determine their strength, are intended for engineers tasked with the rehabilitation of structures that employ scarf joints.

2. Experimental tests

Four scarf joint specimens were replicated to scale from Morgan Bridge using Douglas Fir. The cross-section of the joints was 4 in. by 10 in. and the length was approximately 13 in. (see Fig. 2), although the length outside the joints was extended significantly to avoid interference of stress concentrations resulting from the bolted fixtures. The lower chord of Morgan Bridge was constructed of Hemlock, making wood species (and the lower shear capacity of Douglas Fir) the only significant difference between the original and replicated joints. However, concerns did arise over how to replicate the use of mechanical fasteners present in the bridge joint. Figs. 1 and 2 demonstrate that in the bridge, scarf joints utilize clamping bolts placed transversely through the members at the center of the joint, but the authors wanted to focus on the timber joinery and its associated limit states (e.g. see fracture in Fig. 1), not bolt shear resistance. Therefore, oversized holes and slender diameter bolts were selected and tightened only during assembly; bolts were loosened and left slack during testing to ensure that scarf joint strength was dependent only on the timber.

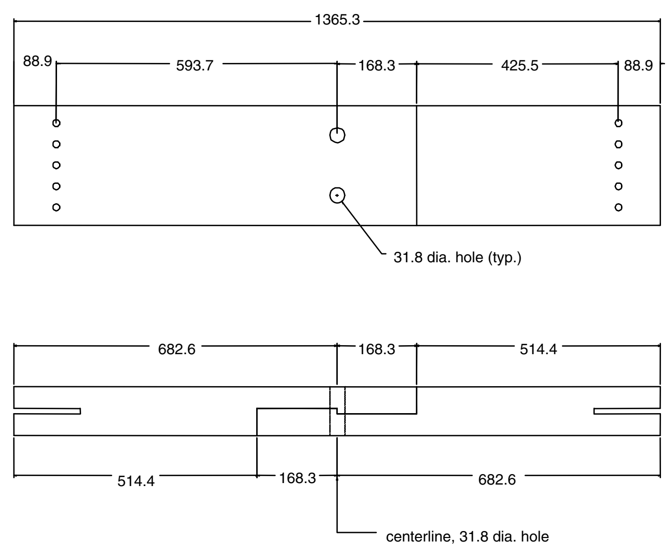

Fig. 2. Halved and tabled scarf joint geometry (in millimeters).

In preparation for testing, the specimens were kept in a temperature and humidity controlled chamber for about three months at 70 °F and 60% relative humidity, allowing the specimens to reach an equilibrium moisture content of approximately 12%. Photographs and detailed measurements were taken to assist in making comparisons of the joint condition before and after testing. The scarf joints were tested in axial tension in a 445 kN (100 kip) MTS Universal Testing Machine in the Johns Hopkins Structural Testing Laboratory.

The typical test assembly, including instrumentation, is shown in Fig. 3. Instrumentation was installed to measure both the axial and lateral deformation of the joint. On the front of the joint (Fig. 3), two axial strain gages (CEA-06-500UW-350) were placed to measure longitudinal strain across the joint near the contact area and a rosette strain gage (CEA-06-250UR-350) measured principal strains