Engineering Structures 31 (2009) 2526–2533

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

The structural behaviour of a pre-stressed column–beam connection as an alternative to the traditional timber joint system

T. Shiratori [a,*], A.J.M. Leijten [b], K. Komatsu [c]

[a] Laboratory of Structural function /Guest Promovendus TU-Eindhoven, Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

[b] Department of Architecture, Building and Planning, Structural Design and Construction Technology, TU-Eindhoven, VRT 9.23, P.O.Box 513, 5600MB Eindhoven, The Netherlands

[c] Laboratory of Structural function, Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

ARTICLE INFO

Article history:
Received 24 December 2007
Received in revised form
10 March 2009
Accepted 4 May 2009
Available online 30 May 2009

Keywords:
Timber joint
Pre-stress
Embedment
Kusabi–Nageshi
Friction
K–N
Post and beam
Timber connection
Seismic retrofitting
Bolt

ABSTRACT

We present a new and alternative proposition for the traditional Asian timber column-and-beam connection, using the Kusabi–Nageshi (K–N) joint system. The mechanical behaviour is complex and relies on the embedment strength of the timber, pre-stress, friction, and elastic energy storage. Using a systematic comparative analysis, the advantages of the K–N joint over more traditional joints can be made clear. The comparison of the hysteresis from cyclic loaded cross-joint tests with varied pre-stress clarifies the enhanced mechanical behaviour of the K–N joint system.

1. Introduction

Traditional Asian timber structures in which the stability is dependent on the moment rotation behaviour of column-and-beam joints, such as the Nuki joint (column centre penetrating beam) or Nageshi joint (column side penetrating beam) shown in Fig. 1 left and centre, have a number of shortcomings. One of most critical among these is the lack of a permanent tight fit between the column and beam, essential for an immediate load take up, which leads to an unpredictable behaviour of the structure. The reasons for the loss of this fit include wood shrinkage, dislocation of wedges, and non-recoverable deformations by seismic impacts. As a solution, a new joint has been developed, namely the *Kusabi–Nageshi* (K–N) timber joint system, details of which are shown in Fig. 1 right [1,2]. The two traditional elements, the Kusabi wedge of the Nuki system and the side penetrating Nageshi beam, have been combined to form a horizontal long wedge–beam system. A penetrating bolt that keeps the elements together can be tightened to make and maintain the pre-stress. A part of the pre-stress is passed on to the embedment areas to enable a firm and continuous fit in both the elastic and post-elastic deformation stages, before, during, and after the seismic loadings. Tight fittings are achieved with more certainty, leading to improved structural performance with immediate load take up, enhanced rotational stiffness, ductility, and energy dissipation.

The use of pre-stress itself in timber structures is not new. For traditional structures, tight fittings achieved by striking-in a type of wedge can be described as applying a pre-stress. The degree of the applied pre-stress is uncertain and solely dependent on the carpenter's judgment, which makes the evaluation of its effectiveness difficult even today. In the long-term perspective, many aspects, such as the moisture content variation, may affect the degree of pre-stress. Another active application of pre-stress and friction in timber structures can be seen in the production of laminated timber bridge decks. High strength steel bars that run through the timber deck laminations introduce those stresses where friction between the laminations transfers the transversal loads. In this application, stress relaxation losses are compensated by a preset re-tightening schedule. The appropriate scheduled re-tightening is reported to maintain 40% of the initial pre-stress

* Corresponding author. Tel.: +81 031 64 424 5085; fax: +81 0774383678.
E-mail addresses: sessiondesign@hotmail.com (T. Shiratori), a.j.m.leijten@tue.nl (A.J.M. Leijten), kkomatsu@rish.kyoto-u.ac.jp (K. Komatsu).

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doi:10.1016/j.engstruct.2009.05.003

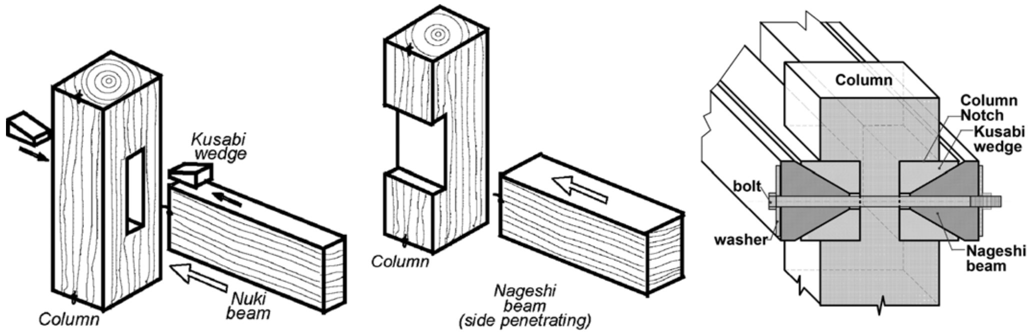

Fig. 1. Traditional Nuki joint (left), Nageshi (centre) and the new K–N joint (right).

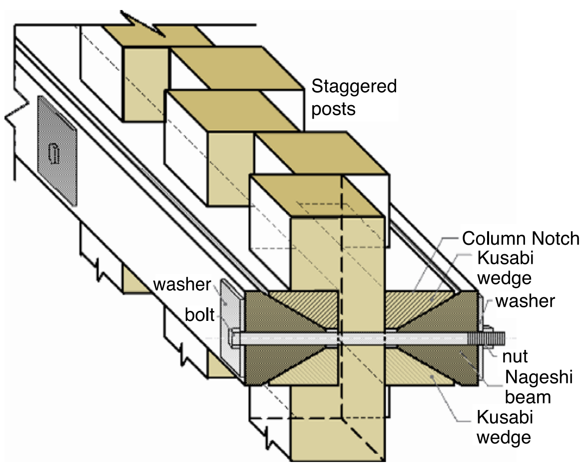

Fig. 2. K–N joint shear wall with staggered columns.

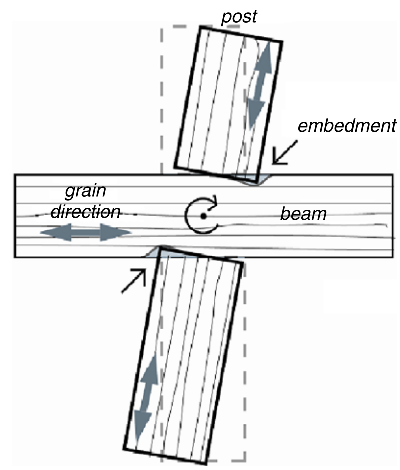

Fig. 3. Embedment and grain direction.

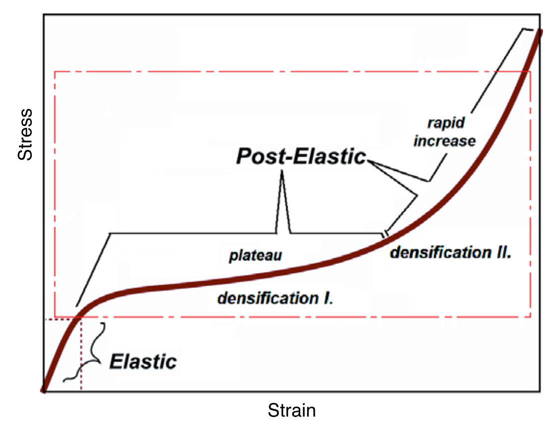

Fig. 4. Partial compression stress–strain curve.

value, even in an outdoor, rather harsh environment [3]. This may also support the effectiveness of the traditional joints mentioned previously, if the wedges are stroked-in periodically. (The investigation of pre-stress losses, and an effective solution to maintain a sufficient pre-stress level of the K–N joint are also critical concerns, but these will be examined in a future report.)

For the K–N joint, the pre-stress and associated friction play a vital role. The major focus of this paper is in the clarification of the influences which the pre-stress, in association with friction, brings to the K–N joint's structural performances. This report clarifies the complex mechanical behaviour of a pre-stressed K–N joint by the following:

(1) Identification of the major resistive mechanisms, namely the embedment, friction, and pre-stress.
(2) Systematic comparative analysis of the moment–deformation hysteresis loops.

2. Mechanical performance of the K–N joint

This K–N joint is aimed at applications in a column-and-beam structure (previously shown in Fig. 1 right). This is a traditional and common form of timber construction in Japan. In an effective staggered composition, the use of underutilized small-sectioned timbers (i.e., 9 cm^2) is also possible. Multiple alignments of the staggered columns bring another application as a shear wall (Fig. 2). This analysis focuses on the behaviour of a single notched column, with a K–N beam joint being the starting point from which the behaviour of multiple K–N joint structural elements may be deduced.

Three important resisting mechanisms that affect the mechanical performance of the K–N joint can be identified, as follows:

2.1. Embedment

The K–N joint follows the traditional Japanese timber column-and-beam joint in its mechanical behaviour [4,5], in which when tightly fitted, the embedment determines the stiffness and strength of the joint. The embedment discussed in this research is a deformation caused as partial compression (meaning not full surface), perpendicular to the grain of the horizontal timber beam (Fig. 3). The stress–strain curve of a partial compressive test, perpendicular to the grain, can be visualized as tri-linear parts (Fig. 4). Since earthquakes consist of repeated cyclic loading, seismic force comes into the joint as both positive (+) and negative (−) rotation, and as a result the embedment shape on the Kusabi wedge will take a convex form (Fig. 5, and Fig. 6, left), caused by non-recoverable deformations. While the rotational deformation