Available online at www.sciencedirect.com
ScienceDirect
Engineering Structures 30 (2008) 2032–2040
ENGINEERING STRUCTURES
www.elsevier.com/locate/engstruct

Experimental study and finite element modelling of Japanese "Nuki" joints — Part one: Initial stress states subjected to different wedge configurations

Z.W. Guan[a,*], A. Kitamori[b], K. Komatsu[b]

[a] *Department of Engineering, University of Liverpool, Liverpool L69 3GQ, UK*
[b] *Wood Research Institute, Kyoto University, Gokasyou, Uji, Kyoto 611-0011, Japan*

Received 5 March 2007; received in revised form 8 January 2008; accepted 8 January 2008
Available online 21 February 2008

Abstract

Initial conditions introduced by different wedges in a traditional Japanese "Nuki" joint affect its stiffness and load carrying capacity significantly. Due to the complicated nature of the problem, no proper measurements have been undertaken historically, nor has there been theoretical modeling of the initial stress state in the joint. This leads to a lack of full understanding in the critical regions where high contact stresses are generated by locking wedges into various engaged positions. There is a need to undertake quantitative studies in those regions in order to make better designs and assist renovation of this type of the joint. In the work described in this paper, a series of experiments has been undertaken to investigate initial strain (and hence stress) states of the "Nuki" joint induced by the use of wedges with a typical angle but various tightnesses. A large number of strain gauges were used to obtain strain distributions in critical areas of the "Nuki" beam element. In Part 1 of the paper, 3-D nonlinear finite element models were developed to simulate the wedge insertion processes and the initial strain (stress) states. Numerical simulations were compared with the corresponding experimental results yielding reasonably good correlation. Racking resistance of the "Nuki" joint will be presented in Part 2.

Keywords: 'Nuki' joint; Wedge; Tightness; Initial strain; Contact stress; Finite element

1. Introduction

The Japanese "Nuki" joint is one of the basic jointing mechanisms used in historical timber constructions such as temples and shrines as well as in modern timber houses [1–3]. This joint has been used for many years for connecting a narrow beam, known as a "Nuki" member, through a relatively thick column member. The "Nuki" member is placed through a rectangular opening in the centre of a column. The vertical size of the opening is larger than the height of the "Nuki" member to allow the member to pass through the column easily on a construction site. In order to lock the joint into position with an appropriate tightness for a practical use, wedges must be inserted and knocked into a reasonably tight position between the "Nuki" member and the cross grain of the opening in the column. Fig. 1 shows a "Nuki" joint in a traditional Japanese temple.

Traditionally, the tightness of the joint created by different wedges is purely determined by accumulated practical experience, with hardly any research or academic studies on the degree of fixation due to wedges. Therefore, it is necessary to undertake thorough research on the initial conditions of the joint before studying its racking behaviour. An experimental approach is essential to obtain first-hand scientific data on local deformations in critical areas of the joint. There are limitations in pure experimental approaches, e.g. it is extremely difficult to obtain deformations in contact areas between the wedge and the "Nuki" beam, and between the wedge and the column. Also it is impossible to measure contact deformations in the critical areas. The most promising way to overcome such limitations is to develop nonlinear 3-D finite element (FE) models, subjected to verification by the corresponding experimental results. Thus the initial strain (stress) states in the joint can be studied in detail in relation to different wedge configurations and species.

In this paper, effects of the initial fixation introduced by wedges on strain distributions at the vicinity of contact

* Corresponding author. Tel.: +44 1517945210; fax: +44 1517945218.
E-mail address: zguan@liverpool.ac.uk (Z.W. Guan).

0141-0296/$ - see front matter
doi:10.1016/j.engstruct.2008.01.003

Table 1
Orthotropic elastic material properties of the beam, column and wedge

Component	E_L	E_R	E_T	G_{LT}	G_{LR}	G_{TR}	υ_{LT}	υ_{TL}	υ_{LR}	υ_{RL}	υ_{TR}	υ_{RT}
Beam	8940	666	398	466	624	41	0.019	0.388	0.029	0.367	0.551	0.335
Column	7240	539	322	378	505	33	0.020	0.408	0.030	0.380	0.580	0.353
Wedge	13340	994	594	696	930	61	0.017	0.347	0.026	0.329	0.491	0.298

MPa for all modulus.

Fig. 1. A typical 'Nuki' joint in a traditional Japanese temple.

surfaces of the "Nuki" member have been investigated through local strain measurements. Numerical analysis based on the nonlinear 3-D finite element method is then developed to simulate the wedge insertion processes and to obtain overall stress and strain distributions in all critical contact areas. FE models are compared with the related test results, which show reasonably good correlation. Contact stress distributions in the 'Nuki' beams and the column are also presented and discussed.

2. Experimental work

The test specimens were composed of a Japanese cedar (Cryptomeria japonica D. Don) column (120 mm × 120 mm cross-section, and 1000 mm length) and 'Nuki' beam (30 mm × 105 mm). Magnitudes of the initial stress were given by four ranks which were related to four different oversizes (or tightnesses) of the wedge as shown in Fig. 2, i.e. 2 mm, 1 mm, 0.5 mm and 0 mm oversize corresponding to various initial stress levels, where 1 mm oversize corresponds to the optimum level [4]. There were five specimens prepared for each wedge oversize and therefore, five corresponding tests were carried out, but with three repeatable results used to work out the averaged value being presented. At the contact zone of the joint, a large number of strain gauges were attached on the "Nuki" surface to measure compressive strains as shown in Fig. 2. Mean modulus of elasticity of the columns parallel to the grain was 7.24 GPa, whilst the similar modulus of elasticity of the "Nuki" beams was 8.94 GPa. Wedges were made of Moabi (*Mimusops djave Engl.*) with a mean modulus of elasticity of 13.34 GPa parallel to its grain as shown in Table 1. Sizes of the wedge were 60 mm in length, 30 mm in width, and with a five degree slope angle.

Both the left and the right wedges were knocked into position with the prescribed tightness by a wooden hammer. The knocking-in processes were taken in turn between the two wedges, with one hand holding the column and other using the hammer. This was almost the same as that in construction practice, except that the column would be held by another person. However, such processes inevitably produced some horizontal displacements either to the right or the left, which generated asymmetrical distributions of normal contact strains in the beam. This phenomenon can be seen later (in Fig. 8).

Strain measurements at locations shown in Fig. 2 are presented with finite element simulations in Section 4 in order to obtain comparisons.

3. Finite element simulation

If purely based on experimental work, it would be almost impossible to obtain strain (stress) distributions within a joint. Assuming elastic behaviour applied, stress distributions on the surface of the "Nuki" beam can be obtained by measuring the corresponding surface strains. However, stress–strain relationships in high stress areas such as the wedge–beam and wedge–column interfaces, where severe contacts occur, are not necessarily elastic. Also, there are stress gradients between the surface and the inner areas. Therefore, it is necessary to develop a numerical model to simulate the joint by using nonlinear finite element analysis. With finite element models validated by the related experimental work, stress and strain distributions in any critical areas of the joint can be investigated.

In this phase of the study, 3-D nonlinear finite element models of the joint were developed using the commercial code ABAQUS [5,6]. Fig. 3 shows mesh generation of the joint. The models developed cover joints with different wedge configurations, i.e. a typical initial angle against various knocking-in distances that give four oversizes of the wedge configuration as shown in Fig. 2. Stress and strain distributions on both surface and central areas adjacent to contact regions are investigated.