Engineering Structures 32 (2010) 2912–2918

Contents lists available at ScienceDirect

Engineering Structures

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

Buckling of reticulated laminated veneer lumber shells in consideration of the creep

H.Z. Zhou, F. Fan, E.C. Zhu [*]

School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China

ARTICLE INFO

Article history:
Received 30 December 2008
Received in revised form
6 May 2010
Accepted 10 May 2010
Available online 20 June 2010

Keywords:
Creep
Buckling
Reticulated shell
Laminated veneer lumber
Finite element

ABSTRACT

The constitutive model of laminated veneer lumber dealing with the creep and suitable for FE modeling was developed, based on the year-long tension and compression tests of laminated veneer lumber. The constitutive model was incorporated into the commercial FE software ABAQUS by developing a user-defined subroutine UMAT. FE models to predict the long-term behaviour of reticulated laminated veneer lumber shells, buckling in particular, were developed. Buckling analysis of single layer reticulated laminated veneer lumber shells with three-directional mesh was conducted. The interdependent relationship between the creep buckling load and the buckling time of the shells was revealed through the analysis, and the safety load against buckling during service life of the shells was defined.

1. Introduction

Laminated veneer lumber (LVL), an engineered wood product widely used in civil engineering, is suitable for constructing large span structures like reticulated shells. Yet buckling of such structures, especially in consideration of the creep of LVL, is a problem that must be addressed. Creep is one of the characteristics that distinguishes timber and wood-based composites from other structural materials. Effect of creep of LVL on the structures is worth investigating to predict the long-term performance, including buckling. This study aims to investigate experimentally the creep of LVL to facilitate establishing of the constitutive model of LVL, and to investigate numerically the buckling behaviour of reticulated LVL shells taking creep into consideration. Hence the term creep buckling is used in this paper.

Studies of creep of wood date back to as early as 1740 when French naval architect Buffon [1] investigated the strength loss of Oak beams under sustained load. Ever since, creep of wood and wood structures has long been a focus of study, prominent work includes the research by Wood [2,3], Liska [4] and research by Madsen and Barrett [5]. All work conducted was on the relationship between duration of load, or creep, and strength of wood. More recently, researchers have mainly conducted testing of creep behaviour of bending members, including beams or floor systems made of engineered wood products [6–10]. These studies usually provided a factor reflecting the ratio of deflection due to creep to deflection under instant loading. The long-term structural behaviour can thus be evaluated by applying such a factor. Buckling of structures is also quite an old topic, with Euler's pioneering analysis of the buckling of an axially compressed elastic rod published in 1757 [11]. Taking creep of material into consideration, the idea of creep buckling was first introduced into analysis of columns by Hilton and Hoff in the 1950s [12], respectively, and recently in analysis of steel structures and reinforced concrete (RC) structures under fire [13–23]. Hamed et al. [23] investigated the time-dependent and thermal behaviour of spherical shallow concrete domes. They found that the creep of material plays an important role in the long-term behaviour of the domes and can lead to the creep buckling of structure. Although there are some published studies of buckling of reticulated wood shells [24,25], so far buckling of wood shells in relation to the creep still remains a problem untouched, despite the fact that creep of wood indeed poses significant effect on the long-term structural performance, including buckling.

In this study, tension and compression tests on the creep of LVL were conducted under an indoor climate for a period of one year. The constitutive model dealing with creep and suitable for numerical modeling of structures was established, and FE models incorporating ABAQUS to predict the long-term structural performance of LVL structures were developed. Analysis of buckling and creep buckling of single layer reticulated LVL shells were conducted, and the relationship between the buckling load and buckling time revealed.

---

[*] Corresponding author. Tel.: +86 451 86283679; fax: +86 451 86282704.
E-mail address: e.c.zhu@hit.edu.cn (E.C. Zhu).

0141-0296/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2010.05.010

Nomenclature

f	strength of LVL
E_0	modulus of elasticity (MOE) of LVL
$\varepsilon(t)$	strain at arbitrary time
ε_e	instant elastic strain
ε_{cr}	creep strain
$\dot{\boldsymbol{\varepsilon}}_{cr}$	creep strain rate
ε_{crr}	relative creep strain
$\sigma(t)$	stress at arbitrary time
σ_0	stress at $t = 0$
$J(t)$	creep compliance
ϕ_i	coefficient of the series with each item representing a Kelvin body
τ_i	retardation time of a Kelvin body
$H(t)$	Heaviside function
$\mathbf{S}_e$	material compliance matrix
$\mathrm{d}\boldsymbol{\delta}$	increment of displacement of structure
$\mathrm{d}\mathbf{R}$	residual force
$\mathbf{K}_T$	tangent stiffness matrix of structure
$\mathbf{K}_0$	linear elastic stiffness matrix
$\mathbf{K}_\sigma$	stress stiffness matrix
$\mathbf{K}_L$	linear displacement stiffness matrix
ω	circular frequency of harmonic load
T	period of harmonic load
λ	load parameter
t	time
t_{cr}	creep buckling time
δ_{cr}	creep buckling deflection
L	span of shell
SL	stress level for creep test or load level for creep buckling

2. Tension and compression test of LVL

2.1. Test of LVL

The Kerto LVL, a prominent Finnish wood product, was used in the testing. Short-term test of LVL was first conducted to obtain the basic mechanical properties like moduli of elasticity (MOE) and the ultimate strengths, thus to provide reference for long-term testing. 15 tension and 15 compression specimens were prepared. In accordance with ASTM D198-05 [26], the specimens for compression were in a size of 38 × 38 × 200 mm; the overall length of tension specimens was 500 mm, with a cross-section in the waisted section of 15 × 15 mm; the gauge length for both tension and compression was all 150 mm. All specimens were conditioned to constant mass at a relative humidity of (65 ± 5)% and a temperature of (20 ± 2) °C.

Both the tension and compression tests were conducted on a versatile testing machine. According to the testing results, the average compression strength was 43.6 MPa, and the MOE was 14 437.4 MPa; the average tension strength was 49.8 MPa, and the MOE was 13 069.7 MPa. The averaged values of tension and compression properties, $f = 46.7$ MPa and $E_0 = 13\,750$ MPa, were used as the reference for long-term testing and for establishing the constitutive relationships.

Long-term tests were conducted in accordance with ASTM D6815-02a [26]. Both tension and compression specimens were subjected to three stress levels, i.e. 0.2, 0.4 and 0.6 time of the averaged strength, with each stress level containing 3 specimens. Totally 9 tension and 9 compression specimens were used. Under a normal indoor climate in Harbin, Northeast China, the tests lasted for one year, from the end of June 2006 to early July 2007, during the period the room was heated from mid-October to mid-April next year. Fig. 1 shows the test set-up for creep of LVL.

Fig. 1. Test set-up for creep of LVL.

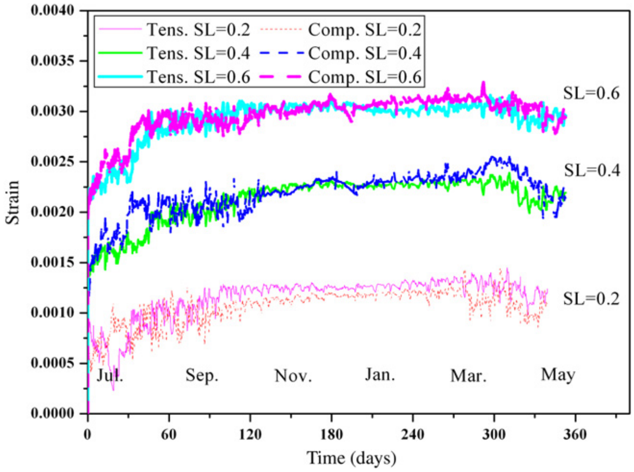

Fig. 2. Creep of LVL under different stress levels.

Fig. 2 shows the strain development against time, where a single curve is the averaged value from 3 specimens under the same stress level. Generally, the creep strain increased with time, although there were some fluctuations due to variations in temperature and relative humidity; the magnitude of creep strain increased with stress level and is almost proportional to the stress level; in the initial stage of about two months, creep strain climbed up rapidly, and then entered the second stage of steady growth. It is worth noting that there was virtually no difference of creep between tension and compression.

2.2. Empirical constitutive model of creep of LVL

In order to predict the long-term performance of structures, constitutive model considering creep of LVL needs to be established. Based on the creeping characteristics from testing, creep