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Experimental and numerical research on gear-bolt joint for free-form grid spatial structures

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ABSTRACT

The nodal connection system for the free-form grid spatial structures should both implement complex-shaped curvature and fulfil the required loading capacity, whilst also meeting various important requirements, such as quick and easy assembly at the construction site. A novel joint system named gear joint with the above advantages, developed for free-form grid spatial structures, is presented in this paper. First, a series of tests was carried out considering different bolt diameters, tooth heights, tooth numbers and ball thicknesses. The different failure modes and whole moment-rotation (M-Φ) curves of gear bolt joints were obtained, and the joint stiffness and strength were investigated. Second, a three-dimensional finite element (FE) model of the joint was established. The comparison between computation and experiments highlights the degree of accuracy of the proposed FE model. The stiffnesses, strengths, rotation behaviours, and failure modes of the new joint system were carefully compared and discussed. Based on the results, the influence rules of the parameters on the mechanical behaviour of the new joint were obtained. Finally, based on the power-function model, the formulae for predicting the M-Φ curves of the joints were established. The M-Φ curves have preferable accuracy compared with the experimental curves.

1. Introduction

Due to their outstanding architectural representation and intense visual impact, single-layer reticulated structures are becoming more popular. Contrary to double-layered reticulated structures, the connector must bear not only axial forces but also the bending moments to ensure structural continuity and integrity. Moreover, since free-form or buildings with complex shape have been introduced to the architecture field, the development of appropriate nodal connection systems has become an essential part of the stability of the whole structure. From traditional spatial structures to the latest single layer free-form spatial structures, the joint system is one of the key crucial aspects, not only for the accommodation of geometry but also for the mechanical behaviour of the whole structure. Free-form spatial structures have been recently designed with complex geometry: the surface of the shell is irregular and doubly curved. To meet the free-form requirements, a computational morphogenesis method for translational surfaces was put forward by combining the geometrical modelling technique and the structural method [1,2].

When designing these single-layer and complex-shaped spatial structures, several important factors should be considered, such as optimal form finding, high-strength material, beautiful appearance and economic cost. At the same time, the optimal design and analysis of the connection systems are important tasks for free-form structures, because the creation and realization of such extraordinary geometries and their continuously changing curvature rely on the angles of the connections' geometries. More importantly, the behaviour of the joints plays a key role in the stability of the whole-grid spatial structures.

Results obtained by Fathelbab [3] showed that the stiffness of the joints had a significant effect on the stability behaviour of a single-layer latticed shells. The experimental study on the single-layer cylindrical reticulated shell carried out by Huihuan et al. [4,5] concluded that the loading capacity of the single-layer latticed shells with semi-rigid joints is between those of the structures with rigid joints and pin joints and that the bending stiffness should be considered when analysing single-layer spatial structures. Buckling collapse and its analytical method of steel reticulated domes with semi-rigid ball joints are discussed by Kato et al. [6], and the reductions in collapse loads due to semi-rigidity of the connections, as well as to the geometric imperfections of nodal coordinates and member crookedness, are investigated. It

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Nomenclature

M	bending moment
Φ	joint rotation
ω_1	horizontal angle of a member
ω_2	vertical angle of a member
ω_3	twist angle of a member
d	diameter of gear bolts
t	tooth depth
n	number of teeth
Φ_1	angle of single tooth
t_n	thickness of the ball
f_y	yield stress
f_u	tensile stress
E	young's modulus of steel material
G	shear modulus of steel material
t_1	thickness of middle plate
t_2	thickness of side plate
t_3	thickness of end plate
t_4	thickness of beam
δ_i	displacement measured at the point i on the specimen
l_{ij}	distance between the points i and j
F	horizontal force
L	distance between force and bolt centre
M_{inf}	elastic-moment resistance
M_{sup}	plastic-moment resistance
$S_{j.ini}$	initial stiffness
$S_{j.p\text{-}l}$	post-limit stiffness (=0.1$S_{\mathrm{j.ini}}$)
Φ_{inf}	elastic-rotation
Φ_{sup}	plastic-rotation
KR	knee range of the M-Φ curve
AVG	average value
$S_{j,ini,num}$	initial stiffness obtained by FE model
$S_{j,ini,exp}$	initial stiffness obtained by test
$S_{j,ini,Eq(4)}$	initial stiffness obtained by analytical model
$M_{sup,num}$	plastic-moment resistance obtained by FE model
$M_{sup,exp}$	plastic-moment resistance obtained by test
M_u	ultimate bending moment
$M_{u,\ Eq(23)}$	ultimate bending moment obtained by analytical model
$M_{u,exp}$	ultimate bending moment obtained by test
n_s	shape parameters of M-Φ curve
ϕ_p	rotation of plates
ϕ_t	rotation of tooth
ϕ_n	rotation of ball node
K_p	stiffness of plates
K_t	stiffness of tooth
K_n	stiffness of ball node
$K_{p,m}$	stiffness of middle plates
$K_{p,s}$	stiffness of side plates
$\phi_{p,m}$	rotation of middle plates
$\phi_{p,s}$	rotation of side plates
$\phi_{t,m}$	rotation of tooth of middle plates
$\phi_{t,s}$	rotation of tooth of side plates
F_s	the forces acting on side plates corresponding to unit bending moment
L_m	length of deformation region on middle plates
L_s	length of deformation region on side plates
A_m	sectional area of deformation region on middle plates
A_s	sectional area of deformation region on side plates
h_p	height of plate
h	margin of plate
h_{eq}	height of equivalent section
$\phi_{ts,m}$	the rotation value in the tooth caused by the shear deformation in middle plate
$\phi_{ts,s}$	the rotation value in the tooth caused by the shear deformation in side plate
$\phi_{tb,m}$	rotation value in the tooth caused by the bending deformation in middle plate
$\phi_{tb,s}$	rotation value in the tooth caused by the bending deformation in side plate
$q_{0,\ m}$	the uniform load acting on the tooth of the middle plate due to moment
$q_{0,\ s}$	the uniform load acting on the tooth of the side plate due to moment
k_n	coefficient of inhomogeneous stress distribution
A_{eq}	area of equivalent section
I_{eq}	inertia of equivalent section
h_0	root section's height of tooth
k_{tb}	reduction coefficients of bending deformation
k_{ts}	reduction coefficients of shear deformation
h_b	end section's height of tooth
h_y	height of yield region in middle plate
Δ_{eqb}	equivalent deformation of tooth under bending load
Δ_{eqs}	equivalent deformation of tooth under shear load
Δ_{ts}	deformation of tooth under shear load
Δ_{tb}	deformation of tooth under bending load
k	shape coefficient of shear stress
q_0	uniform load from the unit moment
h_{eqb}	height of the equivalent calculation under bending load
h_{eqs}	height of the equivalent calculation under shear load
Δ_n	deflection of the centre point of the loading area on the ball node
q_n	uniform load acting on the ball node due to the unit moment
r	radius value of the node ball
I_n	moment inertia of the ball section
M_o	bending moment at point o
F_m	the forces acting on middle plates corresponding to unit bending moment

is verified that for single-layer latticed shells designed in practice, inelastic behaviour in connections, along with the influence of joint semi-rigidness, is very important. Stephan et al. [7] obtained the result that the stiffness in the connection can obviously affect the stability behaviour of the whole free-form spatial structure. Therefore, in order to design a reasonable single layer free-form spatial structures, it is very important to design a reasonable and efficient connection systems with good bending stiffness first.

However, compared with the ordinary framing systems, the connections for these structures are more complicated [8]. In single layer free-form spatial structures, more members, usually more than five members, are connected to a single joint node and the members are positioned in a three-dimensional space, which may cause complexities in the mechanism of force transfer. To provide proper solutions in connection systems for the free-form spatial structures considering structural and geometrical requirements, many companies and researchers have provided different types of joint systems in the past decades. One of the most common types of joint systems in real spatial structures consists of forged steel nodes, sleeves or washers, high-strength bolts and end cones, such as the bolt-ball joint (Fig. 1(a)) and socket joint (Fig. 1(b)) in [9–14]. The previous research is important in the study of mechanical performances of the latticed structures with semi-rigid joints. However, there are two limitations of the bolt-ball joints: (i) the members are usually connected to the ball node through just one high-strength bolt. The bending and shear forces are transmitted from the members to the ball node by one bolt. The stiffness of the joints is weak; (ii) most of the semi-rigid joints are