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Experimental and numerical study on the cyclic performance of the gear-bolt semi-rigid joint under uniaxial bending for free-form lattice shells

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ABSTRACT

To study the cyclic behaviour of a novel gear–bolt semi-rigid joint, quasi-static tests were conducted on seven full-size specimens. The key parameters of the gear–bolt joint investigated in this test include the gear–bolt diameter, number of teeth, and tooth depth to gear-bolt diameter ratio (t/d). A detailed research is carried out to study the effects of these parameters on the hysteresis curves, skeleton curves, degraded characteristics, ultimate capacity, energy-dissipation capacity, and failure mode. The experimental results showed that the hysteresis performance was enhanced with the increasing of number of teeth, gear–bolt diameter, and t/d. In particular, the hysteresis curves were fuller with higher number of teeth; however, an excessive number of teeth should be avoided as it would lead to a brittle rupture of the teeth. The ultimate capacity increased with the increase in the gear–bolt diameter and t/d. of accurate finite-element (FE) models of gear-bolt joint considered the geometry and material nonlinearity was established, and the accuracy of the FE mode was verified by comparison of the computation with test results.

1. Introduction

Because of their outstanding architectural design and superior mechanical properties, single-layer free-form lattice shells have been widely employed in construction projects. The free-form grid lattice shells have recently been designed with a complex structure shape which is irregular and doubly curved. Several important factors should be considered in the design of the single-layer lattice shells with complicated shapes, such as reasonable constructional form, high material strength, aesthetics and construction cost. In addition, optimization design of the joint is significant for free-form lattice shells, which can meet requirements of the creation and realization of such complicated geometries. More importantly, the connections in such structures should be sufficiently strong to withstand the bending moment [1]; the stiffness of the connections has important effect on the stability of the entire structure [2–4]; the actual joint stiffness should be considered during the structural design, as suggested in Eurocode 3, part 1.8 [5].

Over the past several decades, various solutions have been provided for the connection systems in free-form lattice shells. One of the major joint types in actual lattice shells is connected with member by high-strength bolts, such as the socket joint and bolt-ball joint presented in other studies [6–9]. However, two limitations in the bolt-ball joint and socket joint exist. i) Only a single high-strength bolt, which is parallel to the pipe, is used to connect pipes to the ball node. Therefore, stiffness of the joints is poor. ii) Currently, H-shaped or rectangular cross sections are more often used in single-layer grid shell structures. Compared to the cross section of a pipe, the out-of-plane inertia of rectangular cross sections can be increased, which is an advantage for free-form or larger span shells.

For single-layer lattice shells, other main types of semi-rigid joints include two-bolt [10–13] and multiple bolt joint systems [14]. Considering the bolt-column (BC) joint (Fig. 1(a)) as an example in two-bolt joint systems, the members and cone parts are welded in a factory. At the construction site, the members and column nodes are connected by two high-strength bolts, which do not require welding. Angles adjusting between the beam members in the horizontal direction can be achieved by bolt hole on column node; the cone shape can be adjusted to realise the change in the vertical angles. The end-face joint (Fig. 1(b)), which is a typical multiple-bolt joint, comprises a cross-shaped node, cables and bolts. The bending moment can be transferred using the multiple bolts. The horizontal and vertical angle between the short members can be achieved by cutting the node. However, the twist angle of these two joint systems is limited to a certain range. Hence, these joints are applied to small span single-layer free-form lattice shells with a simple shape.

A novel gear joint, which has both good bending stiffness and universal properties, has been developed for free-form lattice shells [15]. Composition of gear-bolt joint is as shown in Fig. 2. Specifically, the gear-bolt joint connects a bolt and a gear, and thus, withstanding the bending moment (Fig. 3). The joints can be used to connect non-circular

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Nomenclature

d	diameter of gear bolt
t	tooth depth
n	number of teeth
t_n	thickness of ball
t_1	thickness of middle plate
t_2	thickness of side plate
t_3	thickness of end plate
t_4	thickness of beam
M	bending moment
Φ	joint rotation
f_y	yield strength
f_u	tensile strength
A_{rea}	area around the bending-moment hysteresis curve
l_{ij}	distance between the points *i* and *j*
δ_i	displacement of point *i* on the specimen
Φ_u	ultimate rotation
Φ_y	yield rotation
μ	ductility
Δ_u	ultimate displacement
AVG	average value
Φ_1	angle of single tooth
E_c	energy-dissipation coefficient
E	Young"s modulus of steel
$S_{j,ini}$	initial stiffness
$S_{j,P\text{-}l}$	post-limit stiffness
F_i	yield force
δ_i/δ_j	the displacements of points D1–D3

cross-sectional members, such as H-shaped or rectangular cross-sectional members. Based on the continuously changing curvature of the lattice shells, middle plate is welded with hollow ball node at a certain angle. Similarly, the side plates, end plate, and members are also welded in factories. At the construction site, the members can be connected to the hollow ball node using gear bolts without any welding. The universal joint can be used in the free-form lattice shells with complicated geometries and at the same time have the characteristics of high bending stiffness, ease of assembly, and high speed of construction.

Ma et al. [15] experimentally and numerically investigated static behaviours of gear-bolt joint based on different parameters. The results show that the gear-bolt joint system exhibiting both good bending stiffness and bearing capacity. In seismic zones, in addition to the carrying capacity and bending stiffness, cyclic behaviours are also important design parameters, particularly the strength degradation and fracture tendency. Hence, to study the cyclic behaviour of a novel gear semi-rigid joint, seven full-size specimens were tested under cyclic loading. Considering the number of teeth, gear–bolt diameter, and t/d, the effects of the parameters on the hysteresis curves, skeleton curves, failure mode degradation characteristics, ultimate capacity, and energy-dissipation capacity were investigated, compared, and discussed comprehensively. Accurate FE models of the gear-bolt joint were developed considering the geometry and material nonlinearity. The experimental results helped in calibrating the FE models, which were used to carry out the parametrical study.

2. Experimental analysis

2.1. Specimens

Seven gear-bolt joints were tested to failure. Fig. 4 and Table 1 present the configurations of the specimens. Three main parameters were varied as shown in Table 1.

A large member section was used in the test to prevent the member from yielding and buckling before the failure of the gear joint. At the same time, the effect of the beam curvature will not influence the measurement of the gear-bolt joint rotation.

Tensile tests were conducted on the specimens and actual material properties of each component was obtained, as listed in Table 2.

2.2. Setup and measurement

Fig. 5 shows the test setup. The half-hollow ball, which was welded with bottom plate, was fixed to the support beam with high-strength bolts. During the total loading stage, following variables were measured:

- A reciprocating force (F) was introduced via a hydraulic jack.
- The bending moment was induced in gear-bolt joint by applying a horizontal load ($M = F \times L$).
- The displacements at the points D1–D3 were measured using linear variable differential transformers (LVDTs) at each load step.

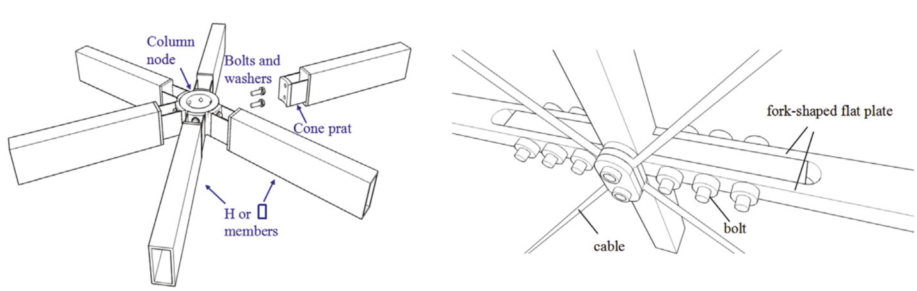
The rotation of gear-bolt joint Φ could be calculated as follows:

$$\varnothing = \frac{\sum_{k=1}^{n} \varnothing_{ij}}{n} \tag{1}$$

$$\varnothing_{ij} = \arctan\left(\frac{\delta_i - \delta_j}{l_{ij}}\right) \tag{2}$$

2.3. Load procedures

Fig. 6 shows the procedure of applying the loads. For each specimen, the loads were applied by controlling the load and displacement in accordance with the basic loading sequence. The tests were conducted



(a) Bolt-column connection (b) End-face joint

Fig. 1. Joints used in single-layer latticed shells.