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Experimental and numerical research on a new semi-rigid joint for single-layer reticulated structures

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ABSTRACT

Recent challenge for large-span single-layer reticulated structures is the development of a new joint that can provide these structures with adequate stiffness while satisfying various important requirements, such as easy assembly on a construction site. In this paper, a new semi-rigid joint system, which is referred to as the bolt-column (BC) joint, is developed. A series of tests was performed considering different thicknesses of the side plates, pretension forces and diameters of the bolts. A three-dimensional finite element (FE) model of the joint was developed to evaluate the bending stiffness, moment resistance, rotational capacity and failure mode of the joint. A comparison between the computations and experiments highlights the degree of accuracy of the proposed FE models. The moment-rotation curves, which can be introduced in the analysis of the structure, were obtained. The stiffnesses, strengths, rotation behaviours, and failure modes of the joints are carefully compared and discussed. Based on the results, the influence rules of the parameters on the mechanical behaviour of the new joint are obtained, which are helpful for engineers and designers.

The results indicate that the application of this type of joint in construction practice is promising. The experimental results are employed to calibrate the finite element models, which are used to conduct a parametric study.

1. Introduction

Reticulated space structures were traditionally designed assuming that the joints are ideally pinned or completely rigid. However, the majority of the joints in spatial structures have a finite stiffness and are semi-rigid; their actual behaviours do not conform to either of the two extremes. Therefore, Eurocode 3 Part 1.8 [1] recognizes the use of semi-rigid joints in addition to two conventional and idealistic joint systems: rigid systems and pinned systems.

Recently, the interest in single-layer spatial structures has significantly increased [2–6]. Considerable efforts were made in previous years to assess the actual responses of reticulated space structures with semi-rigid joints. This process involves an investigation of the mechanical behaviours of traditional semi-rigid joints and the semi-rigidly jointed latticed structures and the development of a design method for latticed spatial structures with semi-rigid joints. First, many studies aim to obtain the moment-rotation curves or the associated properties of some traditional existing joints to enable the incorporation of joint stiffness in the structural analysis. Joint systems that are frequently employed in reticulated structures and experimentally and numerically investigated include the aluminium alloy truss connector [7], the bolt-ball joint system [8–14], the space-truss connector [15] and the socket joint system [16]. Second, both numerical and experimental studies have been conducted to investigate the effect of the stiffness of connections on the behaviours of spatial structures. Fathelbab [8] concluded that connection stiffness has a considerable effect on the load-displacement behaviour of a space structure; the safety and economic benefits of a space structure can be achieved if the effect of the joints is properly addressed during design. Observations from a previous study [17,18] confirmed that connection stiffness had a significant effect on the load-displacement behaviour and failure mode of a single-layer spatial structure. The experimental study by Ma et al. [19] concluded that the loading capacity of a single-layer cylindrical reticulated shell with semi-rigid joints falls within the loading capacities of structures with rigid joints and pin joints and that bending stiffness should be considered for analysing single-layer spatial structures. Kato et al. [20] verified that inelastic behaviour in conjunction with the influence of joint semi-rigidness is more important than imperfection sensitivity for domes designed in practice.

Previous research is important in the study of the mechanical performance of latticed structures with semi-rigid joints. However,

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Nomenclature

d	bolt diameter
L_1	distance between two high-strength bolts
t_1	thickness of front plate
t_2	thickness of side plate
t_3	thickness of middle plate
t_4	thickness of end plate
P_{24}	standard preload of M24 bolt according to the code
P_{27}	standard preload of M27 bolt according to the code
f_y	yield strength of the steel material
f_u	tensile strength of the steel material
E	Young's modulus of steel material
M	bending moment
ϕ	joint rotation
δ_i	displacements measured at the point i on the specimens
l_{ij}	distance between the two points i and j on the specimens
$S_{\mathrm{j.ini}}$	initial stiffness
$S_{\mathrm{j.p-l}}$	post-limit stiffness (=$0.1S_{\mathrm{j.ini}}$)
M_{inf}	elastic moment resistance
M_{sup}	plastic moment resistance
KR	knee-range of the M-ϕ curve; transition zone between the initial and post-limit stiffness
AVG	average value
$S_{j.ini,anal}$	initial stiffness; numerically obtained
$S_{j,ini,exp}$	initial stiffness; experimentally obtained
$M_{sup,anal}$	plastic moment resistance; numerically obtained
$M_{sup,exp}$	plastic moment resistance; experimentally obtained
γ_{M2}	partial safety factor for joint (=1.25)
f_{ub}	ultimate tensile strength for bolts
$F_{t,Rd}$	tension resistance of the bolt
M_b	bending capacity carried by the high-strength bolts
M_{sp}	plastic moment capacity of the side plates
H	height of the front plate
A_s	tensile stress area of the bolt

two limitations exist in previous studies: (i) when the semi-rigid joints in the previous reference are employed in real structures, the members are usually connected to the ball node by one high strength bolt. Therefore, the stiffnesses of the joints are weak, as shown in [21]; when the structure span is 40 m and the rise to span is 1/8, the critical load of the structure with a semi-rigid bolt-ball joint is only 24% of the critical load of the rigid structure; (ii) The members that are employed in the majority of single-layer latticed structures are circular pipes. Compared with the traditional circular tube, members with H, I and cubic sections are also suitable choices for constructing single-layer lattice structures. However, the majority of semi-rigid joints are designed for circular members. With the exception of the joint in [22,23], few studies have addressed joints that are suitable for connecting H and I section members.

Therefore, the main concern of engineering science in recent years is not the problem of structural design methods or analysis models but an appropriate joint design that can provide a structure with adequate stiffness, connect different section pipes, and satisfy other important requirements, such as easy erection and economic advantages. In this paper, a new semi-rigid bolt-column (BC) joint for connecting H, I and rectangular section members is developed, and a series of tests on the new joint system is performed. The basic characteristics of this type of connection, such as the bending stiffness, rotation and moment capacity, and the failure mode are investigated. The results show how the combination of different parameters can improve the stiffness of a joint and its rotational capacity.

2. Bolt-column (BC) joints

The bolt-column (BC) joint system is composed of a hollow column node, high-strength bolts, washers, and an end-cone part. It can be used to connect H, I or rectangular members in real structures, as shown in Fig. 1.

The end-cone part consist of five plates: one front plate, one middle plate, two side plates and one end plate. The cone parts are welded at both ends of the members in the factory. At the construction site, the two high-strength bolts are used to connect the members to the column node without any welding work. All holes in the hollow column are taped to accommodate the threaded part of the bolts. The two high-strength bolts are screwed into the hollow column node from the end-cone part. One concave washer is employed at each bolted connection; they are placed at the outside of the column node. The washers smoothly transmit axial compressive or tensile force. The high competitiveness of the joining technologies is related to the high bending stiffness, easy assembly, machining reduction, and high speed of construction.

3. Experimental program

3.1. Specimens

A total of 14 BC joint specimens were tested to failure under monotonic loading. The configurations of the specimens are shown in Fig. 2 and Table 1. The inner diameter and outer diameter of the column node of all specimens were 200 mm and 300 mm, respectively. For each of the geometrical combinations in Table 1, two specimens were tested.

Three main parameters varied among the different sets:

(i) The thicknesses of the side plates: three different thicknesses-3.5 mm, 5.5 mm and 9.5 mm-were employed in the specimens S1-A, S2-B and S3-A, respectively, in the tests.
(ii) The pretension value in the bolts: the pretension forces P_{24} = 225 kN for the M24 bolt of class 10.9 were applied in the specimens S1-A, S2-B and S3-A with the specified tightening torques. Considering the actual situation in the construction site, the pretension force in the bolts varied. Therefore, the specimens S2-A, S2-C and S2-D with $1.25P_{24}$, $0.75P_{24}$, and $0.32P_{24}$, respectively, were considered in the tests to investigate the effect of the pretension force on the mechanical behaviours of the joints.
(iii) The bolt diameter d_1: two different bolt diameters-24 mm and 27 mm-were employed in the test. M24 bolts were used in the specimens in the S1–S3 groups, and M27 bolts were used in the specimens in the S4 group.

The larger section of the tube is provided in the test to prevent instability and local buckling in the tube prior to failure of the connections.

The steel in the beam member, cone part and washers is grade steel S235. The bolts are frictional high-strength bolts (class 10.9). The material properties of the steel were obtained from tensile tests on coupons and the bolt certificate of quality, as shown in Table 2. The material properties of the plates vary with thickness; therefore, different tensile tests were performed based on different