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Finite element analysis and moment resistance of ultra-large capacity end-plate joints

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ABSTRACT

The ultra-large capacity end-plate joints, which can be applied in steel structures involving large spans or heavy loads, can provide larger moment resistance than ordinary end-plate joints or large capacity end-plate joints. However, the existing design methods of the ordinary or large capacity end-plate joints cannot be adopted for this new joint form directly because of the inhomogeneous distribution of the tensile loads carried by the bolts as well as the complex stress state in the end plate. Finite element models were built and validated to be reliable using the existing test results. The performance of the ultra-large capacity end-plate joints was analyzed with these models, and a yield line model of the end plate in the tension side was proposed according to the results. Based on the proposed yield line model, a method to predict the moment resistance of the ultra-large capacity end-plate joints was proposed. The moment resistance obtained by the proposed method was compared to the yielding moment of the finite element models, and the proposed method was proved to provide a conservative result which is safe to be applied in the design of this kind of joint.

1. Introduction

The bolted end-plate joint is widely adopted as moment-resistant beam-to-column joint in the situation where the field welding is not allowed or preferred. The conventional extended end-plate joint arranged four bolts in the tension side, and the moment resistance is limited by an upper boundary controlled by this bolt number when the beam section keeps unchanged. When the resistance demand is larger than this upper boundary, the large capacity end-plate joint with 8 bolts in the tension side can be applied to obtain a larger resistance [1–3]. If the moment resistance of the large capacity end-plate joint still cannot meet the requirement, the number of the bolts in the tension side should be further increased to 12 or 16, and such a joint form is referred to as ultra-large capacity end-plate joint [4], which means this joint form is expected to develop larger capacity than the large capacity end-plate joints.

Considerable experimental studies have been conducted for conventional extended end-plate joints [5–7]. Researchers verified the validity of the numerical method based on experimental results, and analyzed the performance of end-pate joints with different configurations or different parameters with finite element models (FEMs) [8–13]. Several methods to predict the moment-rotation curves have been proposed based on the experimental or numerical researches [14–17], and practical design methods have been specified in the Chinese code, the American code and the Eurocode [18–21]. However, the design methods in these codes share an assumption that the distribution of tension force carried by the bolts is uniform or linear, which is not applicable in the ultra-large capacity end-plate joint because of the significantly inhomogeneous distribution of bolt force increments according to the test results [4]. Also, in these codes planar analysis such as the T-stub analysis is adopted to check the thickness of the end plate, which cannot be employed in the ultra-large capacity end-plate joints directly due to the biaxial bending of the end plate.

For the large capacity end-plate joints, a design method aimed at the long end plate configuration with end-plate stiffeners based on the investigation in reference [1] is provided in the American code [19,20]. Also, the component method in the Eurocode could be applied in the design of the large capacity end-plate joint in theory [16]. However, these methods still cannot be used directly in the design of the ultra-large capacity end-plate joints because the problems caused by the inhomogeneous distribution of bolt force increments and the biaxial bending of the end plate still cannot be solved.

Nevertheless, the design procedure in the existing codes presents basic steps to design bolted end-plate joints with the ultra-large capacity end-plate joint included. In the American code and the Chinese code [18–20], the extended end-plate joints are designed as rigid joints so only the moment resistance needs to be checked. In these two codes, the moment resistance is decided by the designed tensile force of all the bolts in tension with an equivalent lever of force specified as the distance between the centerline of the two beam flanges, and the least thickness of the end plate should be checked based on T-stub analysis. Also, a similar approach could be adopted to calculate the moment resistance of the ultra-large capacity end-plate joints.

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Four full-scale specimens have been tested subjected to monotonic loads to study the performance of the ultra-large capacity end-plate joints, and the results, as well as the detail of the experiments, can be found in reference [4]. However, these experimental data, which are difficult to supplement due to limitation of time cost and economic cost, are not sufficient to present a comprehensive view of this new joint form. Therefore, FEMs established with the software ABAQUS were employed to further study the performance of the ultra-large capacity end-plate joints. Also, a method to determine the moment resistance of the ultra-large capacity end-plate joint was proposed based on the analysis.

2. Finite element models

2.1. Parameters

Totally 24 FEMs of the ultra-large capacity end-plate joints, with two bolt layouts, three bolt diameters and four end-plate thickness considered, were established by using ABAQUS and named as shown in Table 1. The two bolt layouts as well as the dimensions of the end plate are illustrated in Fig. 1. The identifier of each FEM was constituted of a sequence number, the end-plate thickness, the bolt nominal diameter and the bolt layout type. For instance, F1-EP32-M30-A represents the first FEM with a 32 mm thick end plate and M30 bolts, and the bolt layout A is applied. Models F1–F4 were established to simulate the specimens of the experiments in reference [4] and all the parameters in these models were based on the corresponding specimens, whereas the other 20 models were designed to analyze the influence of the parameters to the moment resistance and the rotational stiffness of the investigated joints. The sections of the beams and the columns in the FEMs were H800 × 500 × 60 × 30, which were coincident with the experimental specimens. All the dimensions and details in the models, such as the configuration of stiffeners and pitches of the bolts, were the same with that of the specimens except for the changed parameters. The bolts were established based on the effective diameter in the threaded section, and the effective diameters of M24, M27 and M30 bolts are 21.2 mm, 24.2 mm and 26.7 mm, respectively.

The constitutive relationship of the steel plates in the FEMs was simulated by a multilinear model as illustrated in Fig. 2(a). The FEMs F1–F4 were established to simulate the tests in reference [4] exactly so that all the parameters in constitutive models in these FEMs were designed to

Table 1
Summary of the connection parameters in the specimens.

Model	t_{ep}(mm)	d_b(mm)	Bolt layout	K_φ(10^6 kN·m)	M_y(kN·m)
F1-EP32-M30-A	32	30	A	1.282	3953.7
F2-EP25-M30-A	25	30	A	0.969	3106.0
F3-EP32-M27-A	32	27	A	1.209	3584.8
F4-EP32-M30-B	32	30	B	1.310	3821.9
F5-EP32-M27-B	32	27	B	1.295	3005.0
F6-EP32-M24-B	32	24	B	1.268	2425.3
F7-EP25-M30-B	25	30	B	1.062	3260.0
F8-EP25-M27-B	25	27	B	1.047	2812.5
F9-EP25-M24-B	25	24	B	1.039	2334.6
F10-EP28-M30-B	28	30	B	1.175	3570.3
F11-EP28-M27-B	28	27	B	1.219	2897.4
F12-EP28-M24-B	28	24	B	1.146	2404.0
F13-EP36-M30-B	36	30	B	1.414	3849.6
F14-EP36-M27-B	36	27	B	1.393	3027.0
F15-EP36-M24-B	36	24	B	1.362	2432.0
F16-EP25-M27-A	25	27	A	1.019	2891.1
F17-EP25-M24-A	25	24	A	0.983	2501.9
F18-EP28-M30-A	28	30	A	1.154	3632.4
F19-EP28-M27-A	28	27	A	1.122	3094.3
F20-EP28-M24-A	28	24	A	1.060	2675.6
F21-EP32-M24-A	32	24	A	1.147	2859.7
F22-EP36-M30-A	36	30	A	1.354	4216.7
F23-EP36-M27-A	36	27	A	1.294	3543.5
F24-EP36-M24-A	36	24	A	1.220	3008.1

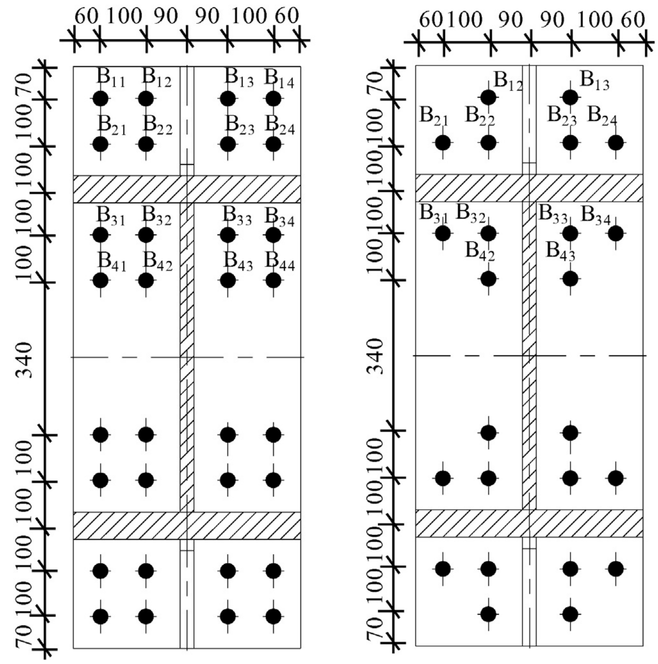

Fig. 1. The bolt layouts of ultra-large capacity end-plate joints: (a) bolt layout A; (b) bolt layout B (units: mm).

be the same with the corresponding specimens in the tests, and the parameters in the constitutive models of other FEMs were designed to be the same with the standard specimens 1-EP32-M30-A to analyze the influences of the changed parameters. The parameters in Group 1 were based on the coupon tests of the 30 mm thick plate and applied in all flanges and webs in beams and columns as well as the stiffeners in the models. The parameters in Group 2 were obtained from the coupon tests of the 25 mm thick end plate and applied in the end plate of F2 to simulate the experiment exactly. The parameters in Group 3 were based on the coupon tests of the 32 mm thick end plates and applied in the end plates of all the models except for F2. For the constitutive relationship of the bolts, a trilinear model was applied as illustrated in Fig. 2(b) [12]. According to the quality certificate of the bolts applied in the experiments, the Young's modulus is 206 GPa, the tensile strength f_u is 1175 MPa and the ultimate strain ε_u is 0.12 for both M30 bolts and M27 bolts, and the yield strength f_y for M30 bolts and that for M27 bolts are 1045 MPa and 1020 MPa respectively so that the yield strains are 5.07×10^{-3} and 4.95×10^{-3}, respectively. In the FEMs, the constitutive parameter of bolts was decided based on M30 bolts for all models except F3, which took the parameters according to M27 bolts in order to be comparable with the corresponding specimen.

The element types employed in the FEMs were three-dimensional 8-node solid reduced integration element C3D8R and three-dimensional 6-node solid element C3D6. A view of the typical mesh is shown in Fig. 3. A finer mesh was defined for the end plate, as the contact analysis allowed [22], to obtain a more accurate end-plate deformation. All the contacts in the bolted connections were simulated with an interaction property defined in ABAQUS, including the contact between the end plate and the column flange, the contacts between the bolt heads or nuts and the end plate or column flange, and the contacts between bolt shanks and the walls of the bolt holes. The normal property of these contacts was defined as hard contact, while the target property was simulated by penalty function with a friction factor of 0.5. Such a friction factor was decided according to the Chinese code based on the steel surface treatment of shot blasting for the experimental specimens [18]. The beam, the end plate and end-plate stiffeners were established as a part, while the column and the continuity plates were established as another part. The two parts were connected by pretensioned bolts with