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The effect of the bolt spacing on the performance of the steel-aluminum composite mullions of curtain wall

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A R T I C L E I N F O

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A B S T R A C T

The main purpose of this study was to investigate the effect of the spacing of through bolts on the performance of the steel-aluminum composite mullions (SACM) using finite element analysis, and the equations for the stress and composite stiffness at the midspan of the SACM considering the coefficient of shear resistance η were proposed. The results shown that the ultimate bearing capacity of the SACM with a full composite action is increased by 18% and 65% as compared with that of the SACM with no composite action and the pure aluminum alloy mullion. The deflection at the midspan of the SACM decreases with the bolt spacing decreases, indicating that the stiffness of SACM increase with the bolt spacing decreases, because SACM can enhance the material utilization of aluminum alloy and the capability of cooperative work of steel and aluminum alloy, in addition, the bolt spacing that equals a third of the span is sufficient to allow the steel and aluminum to have a desired composite action. The equations for the stress and composite stiffness at the midspan of the SACM under the condition of partial shear connection are derived, and the results calculated from these equations agree well with that obtained by the finite element method.

1. Introduction

A curtain wall is an outer covering of a building which is hung from the main structure and is essentially non-load bearing. Thus, the curtain wall does not carry any dead load from the building other than its own dead load, and the loads imposed on the curtain wall are transferred to the building structure through the anchors which attach the mullions to the building [1,2]. Aluminum is the material of choice for mullions from an engineering and design standpoint because of its excellent physical characteristics and relatively light weight [3]. A large number of high-rise buildings with glass curtain walls have been constructed in cities due to the scarcity of land and an increasing demand for housing. This poses particular challenges for the use of aluminum for mullions because of their load bearing properties [4–7], resulting in an increase in the cross section of the mullions, and consequently the decrease of the space of the building and the increase of the construction cost. A possible way to solve these problems is to add steel reinforcement to the aluminum mullions, as shown in Fig. 1. In real applications, in order to ensure the performance of the composite action of the steel-aluminum composite mullions, composite mullions were bolted together by the through bolts for resisting the shear force [8]. In most cases, these through bolts are often arranged merely by rule of thumb of the designers [9], because this conjecture is presented as essentially self-evident without rigorous theoretical justification, the ASCM can not fully exploit the best composite qualities in fact, the full composite action is difficult in these situations, its composite action is usually intermediate between the two extreme limits of no composite action and full composite action, which is termed partial composite action.

Several formulas have been proposed for the SACM under two extreme conditions [10–16]: no shear connection (no shear connection is provided between the steel and aluminum mullion, the two components will work independently, which is referred to as “non-composite” in this study) and full shear connection (the connection between the components is able to fully resist the forces applied to it, which is referred to as “full composite” in this study). Unfortunately there is no generally accepted specification or standard for the application of the steel-aluminum composite structure in the construction of curtain walls [17]. So the internal force and deflection of SACM are often calculated under the assumption of non-composite or full composite. To our knowledge, the research works focusing on the calculation of the internal force and deflection of SACM under the condition of partial composite action had not been presented until now.

The main purpose of this study was to investigate the effects of the spacing of through bolts on the performance of the SACM using finite element analysis, and the coefficient of shear resistance η was proposed to evaluate the composite action of the SACM.

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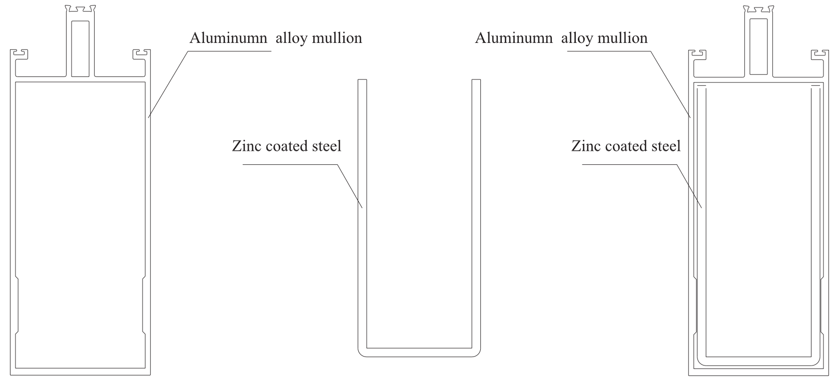


(a) aluminum alloy mullion **(b) zinc coated steel** **(c) SACM**

Fig. 1. The cross section of (a) aluminum alloy mullion, (b) zinc coated steel, and (c) SACM.

2. Finite element model

2.1. Geometric modeling

The finite element model of the SACM was established by ABAQUS, as schematically shown in Fig. 2. In this model, all the initial gaps between the contact surfaces of the members were fixed to be zero, except for that between bolt shanks and holes. In addition, the bolt shank was assumed to be located at the geometric center of the bolt hole, and the bolt shank and head were taken as a single member. The element type used was C3D8R, which is an 8-node, linear brick element with reduced-integration and hour-glass control in ABAQUS. The finite element model as shown in Fig. 3. The boundary conditions of the finite element model are simply supported constraints along x, y, z direction.

2.2. Materials and constitutive relations

The SACM model consists primarily of aluminum alloy, steel and bolts, the properties of which are shown in Table 1. The constitutive behavior of aluminum alloy can be described by the *Ramberg-Osgood* constitutive equation [18]: $\varepsilon = \frac{\sigma}{E} + 0.002(\frac{\sigma}{f_{0.2}})^n$, where E is the elastic modulus at the origin, $f_{0.2}$ is the yield strength, and n can be calculated by the approximate formula derived by Steinhardt *et al.* [18]: $n = f_{0.2}/10$ ($f_{0.2}$: MPa).

The constitutive relations of the steel and bolts are shown in Fig. 4.

2.3. Arrangement of bolts

To investigate the effect of bolt spacing on the properties and performance of the SACM, the finite element models of 10 SACM with different bolt spacings were established as described in previous section. The span (the distance between the centers of two adjacent supports) of all mullions is 3300 mm, and the bolt spacing for each model is shown in Fig. 5 and Table 2, where Model L-00 is the aluminum mullion without bolt connection, Model L-0 is the SACM without bolt connection (no composite action), Models L-1 to L-7 are the SACM with different bolt spacings (partial composite action), and Model L-8 is the SACM with full composite action.

3. Finite element analysis results

3.1. Load and measurement points

The measurement points are shown in Fig. 6 in this study. According to the *Technical Code for Glass Curtain Wall Engineering JGJ102-2003*, the deflection at the midspan of the SACM was calculated under only wind loads, while the stress was calculated under the combination of wind and seismic loads, and the axial force from the dead load of the mullions was neglected in the calculation [14,19–22]. The different standard values of wind load were applied to the ten models described in Fig. 5 and Table 2, we can obtain the results of the deflection at the midspan of the SACM, as shown in Table 3. For the mullion with a span of 3300 mm, the limit deflection of aluminum alloy mullion is $d_{af,\ lim}$ = l/180 = 18.33 mm, and that of steel mullion is $d_{af,lim}$ = l/250 = 13.2 mm, respectively, as stipulated in the specification [23]. In this study, the limit deflection is reached at a wind load of 5 N/mm for Model L-00, and at a wind load of 8 N/mm for Model L-0 to L-8, respectively.

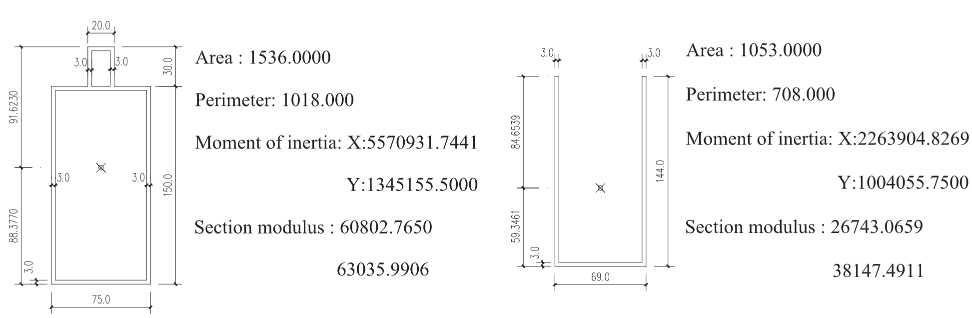
According to the results as shown in Table 3 and the Eq. (1) – Eq. (2), we can obtain the design load values (the combination of the different wind and the same seismic loads) corresponding to the standard values of the wind load, as shown in Tables 4, 5.

$$q = \psi_W \gamma_w q_w + \psi_E \gamma_E q_E \quad (1)$$

ψ:Coefficient for combination value of load

γ: Partial coefficient of load

$$q_E = \beta_E \alpha_{\max} G_{AK} \quad (2)$$



(a) Geometric characteristic of Aluminum alloy **(b) Geometric characteristic of Steel**

Fig. 2. The cross section of the SACM.