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An Equivalent Spring Model for High-vertical Standing Seam Metal Cladding Systems

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SUMMARY

The commonly used high-vertical standing seam metal cladding system (SSMCS) is susceptible to uplift wind pressure due to its weak seam-clip connection. The mechanical behavior of this connection is very complex, and understanding it is crucial for the effective wind resistance design of systems. To investigate this behavior, a series of tensile experiments are conducted using specially designed fixtures in this paper. Based on the measured mechanical behavior, an equivalent spring model for the seam-clip connection is developed. To validate the developed equivalent spring model, experiments on a double-span sheet model (DSSM) and the corresponding finite element analysis are then performed. Comparative studies show that the deformation of the metal sheet obtained from the finite element model incorporating the developed model is in good agreement with that observed in the DSSM experiment. Furthermore, the relationship between the mid-span displacement and tensile force also coincides well. These findings indicate that the equivalent spring model is feasible for evaluating wind-induced structural response of the high-vertical SSMCS.

Keywords: standing seam metal sheet systems, equivalent spring model, tensile test, finite element analysis

1. INTRODUCTION

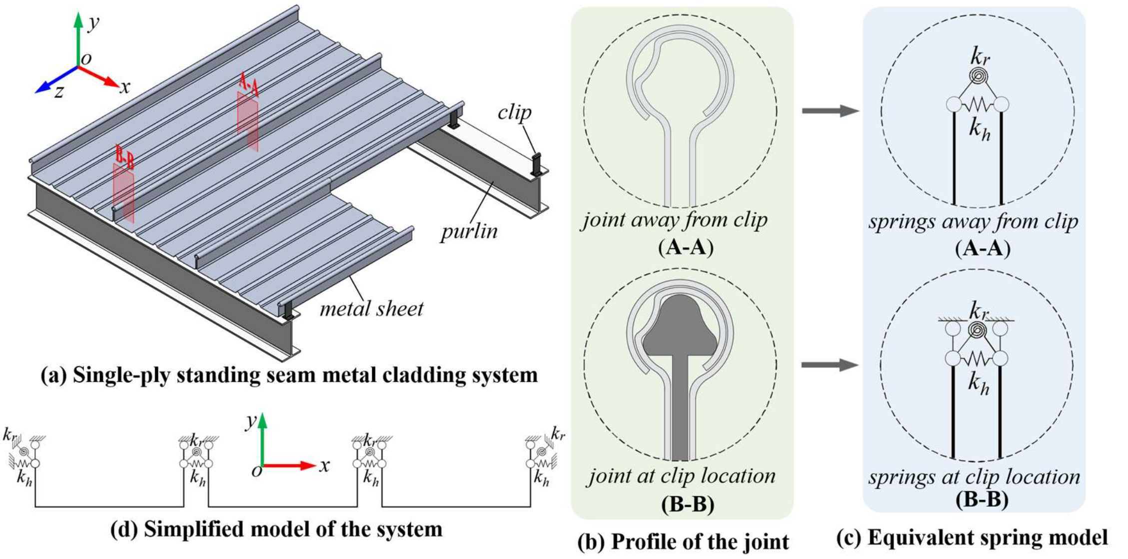
Due to the weak seam-clip connection, SSMCS is sensitive to the uplift wind pressure. Recently, the wind-induced failures of SSMSS have been frequently reported, posing a serious threat to its interior and surrounding environments. Therefore, it is of great social-economic significance to accurately evaluate the performance of the SSMSS for its wind-resistance design

During the past two decades, many scholars have studied the wind resistance performance of the SSMCS via experiments (Surry et al., 2007; Morrison and Reinhold, 2015) and the finite element method (Ali et al., 2003; Min et al., 2021), and they have provided many valuable references for the preliminary design of SSMCS against uplift wind loads. Especially, EI Damatty et al. (2003) proposed an equivalent spring model of high-trapezoidal SSMCS based on the study of the mechanical behavior of the seam. The structural responses of FEM with the equivalent spring system coincide well with those of the full-scale test. However, it should be noted that the parameters of the spring stiffness in their research are only suitable for the specific system. The mechanical behavior of the seam-clip connection of the high-vertical SSMCS differs significantly from that of the high-trapezoidal SSMCS, which has been rarely reported and investigated. This impedes a comprehensive understanding of the wind resistance performance of the high-vertical SSMCS.

Based on this, the aim of this paper is to propose an equivalent spring model for seam-clip connection of high-vertical SSMCS combined with experimental research and finite element analysis.

2. EQUIVALENT SPRING MODEL FOR HIGH-VERTICAL SSMCS

The configuration of high-vertical standing seam metal sheet systems is shown in Figure 1. To conveniently evaluate the performance of SSMCS, the seams are simplified as a continuous spring model with a horizontal component (k_h) and a rotational component (k_r) to simulate the stiffness provided by the horizontal and rotational mechanical behavior of the seams, respectively. In addition, the connection between T-shaped clips and seams is simplified as a discrete vertical spring having stiffness(k_v). These springs are referred to as the equivalent spring model of SSMCS as described in Fig.1. The stiffness of the developed equivalent spring model is calibrated in Section 3, based on the mechanical behavior of the seam-clip connection.



(a) Single-ply standing seam metal cladding system

(d) Simplified model of the system

(b) Profile of the joint

(c) Equivalent spring model

Figure 1. Equivalent spring model establishment for the high-vertical standing seam metal cladding system

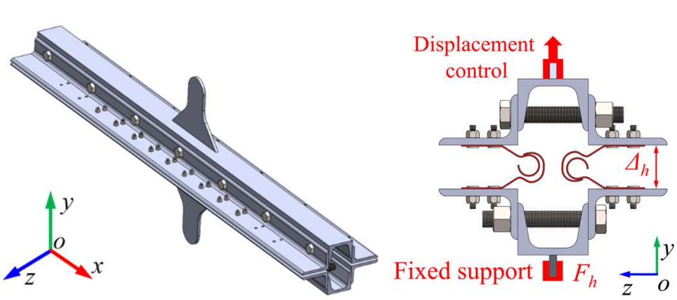
3. TENSILE TEST OF SEAM-CLIP CONNECTION

The stiffness of the horizontal and rotational springs in the equivalent spring model was calibrated separately using sets of specially designed fixtures via tensile tests, based on the assumption of complete decoupling.

3.1 Horizontal behavior of seam connection and its spring stiffness calibration

The fixture used to investigate the horizontal mechanical behavior is demonstrated in Fig. 2. The specimens were fixed along the fixture. During the test, the lower end of the fixture was clamped and the upper end was driven by displacement by a hydraulic tensile test machine. The relationship between tensile force (F_h) and displacement (Δ_h) of specimens was recorded synchronously until the specimens failed. From Fig. 3, it is found that the tensile force increases with the displacement, and the failure displacement is about 45mm. The mean curve can be divided into two ranges, i.e., the linear and non-linear ranges, and their stiffness k_h can be calibrated as follows:

$$dk_h=\frac{dF_h}{d\Delta_h} \tag{1}$$



(a) the initial state (b) the deformation state

Figure 2. Schematical diagram of the tensile test for horizontal mechanical behavior investigation

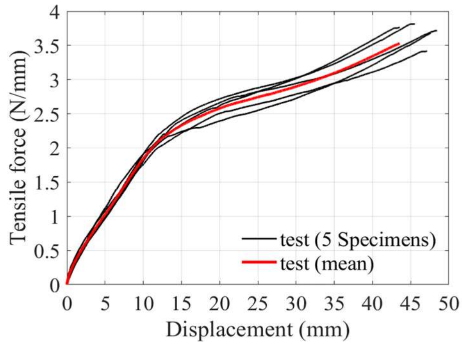
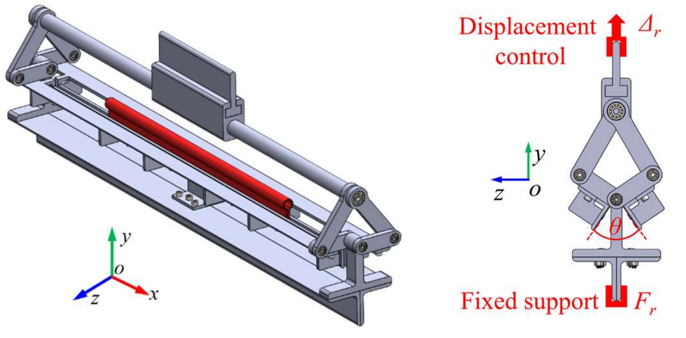


Figure 3. Relationship between displacement and force in the horizontal direction

3.3 Rotational behavior of seam connection and its spring stiffness calibration

The fixture used for investigating the rotational mechanical behavior is shown in Fig. 4, which is fixed and controlled in the same way as the horizontal tensile test. The displacement Δ_r of the and the tensile force F_r are collected synchronously during the test. To clearly illustrate the rotational behavior, the relationship between rotational angle θ and the moment M_r was obtained from the displacement and tensile force based on the geometrical relationship of the fixture. Due to the effect of preload of specimens, this relationship should be modified to obtain a realistic representation of the rotational mechanical behavior. The modified mean curve is depicted by the solid blue line in Fig. 5, and the stiffness k_r can be calibrated as follows:

$$dk_r = \frac{dM_r}{d\theta} \tag{2}$$



(a) the initial state (b) the deformation state

Figure 4. Schematical diagram of the tensile test for rotational mechanical behavior investigation

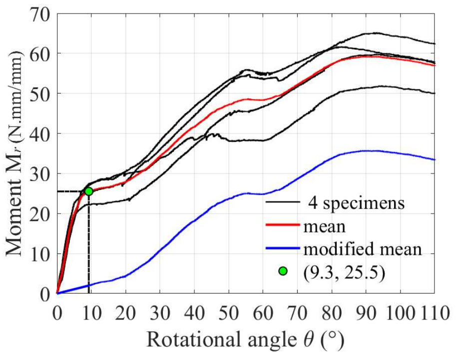


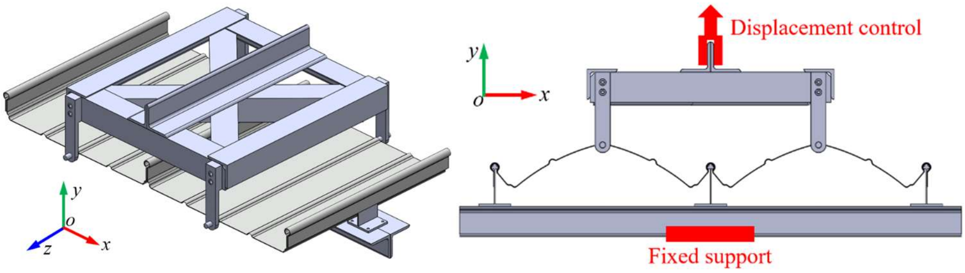
Figure 5. Relationship between rotational angle and moment in the rotational direction

4. VALIDATION OF THE EQUIVALENT SPRING MODEL

In this section, the validation of the equivalent spring model was performed by comparing the structural response from DSSM experiments and corresponding finite element analysis.

4.1 Double-span sheet model experiment

The double-span sheet model is illustrated in Fig.6. The fixture fixation, control, and data acquisition procedures were performed in the same manner as the stiffness calibration test. From Fig. 8, it can be seen that there is a distinct steep drop in the tensile force at a mid-span displacement of approximately 115 mm to 135 mm, indicating the failure of the metal sheet.



(a) the initial state (b) the deformation state

Figure 6. Schematical diagram of the double-span sheet model experiment

4.2 Numerical simulation of finite element model with the equivalent spring model

The numerical simulation of the finite element model (FEM) with the equivalent spring model is performed in this section. As shown in Fig. 7, the displacement distribution from FEM is in good agreement with that observed in the DSSM experiment. In addition, as can be seen in Fig. 8, the displacement-tension force from FEM is also in agreement with that from the DSSM experiment. These results indicate that the developed model is feasible for evaluating the wind-induced structural response of high-vertical SSMSS.

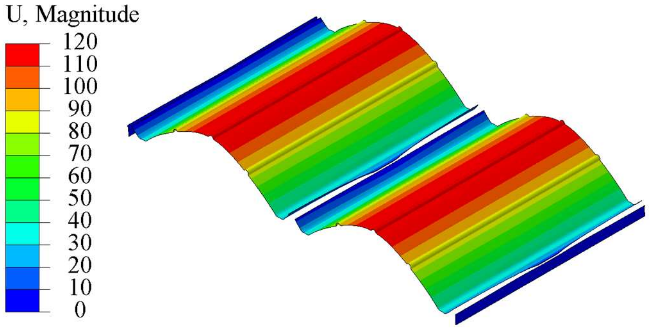


Figure 7. Displacement distribution from FEM

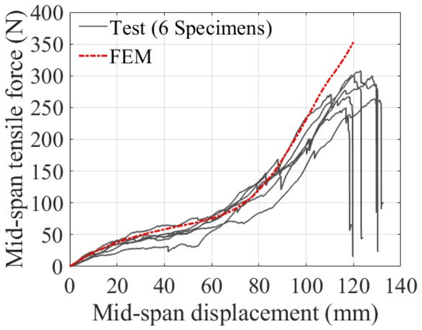


Figure 8. Structural response from test and FEM

5. CONCLUSIONS

This study proposes the equivalent spring model for the seam-clip connection of high-vertical SSMCS. The stiffness of the developed model is calibrated based on the mechanical behavior from the tensile experiment. The numerical simulation shows that the finite element model with the equivalent spring model can provide a reasonable estimation of the structural response compared to the DSSM experiment. It is expected that the equivalent spring model can further be used to evaluate the wind-induced structural response of the high-vertical SSMCS.

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