

Numerical investigations of the connections between cold-formed steel curtain walls and reinforced concrete slabs

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Abstract. Cold-formed steel curtain wall is a very practical way to protect building from variety of external impacts, such as wind, seismic load, rain, temperature difference etc. This paper is focused on structural aspects of the curtain wall design, specifically on the design of the bolted connections between cold formed steel and concrete slab. External walls of high-rise buildings are subjected to significant wind and ice loads. The paper is based on the experimental and numerical research of the connections. It is important to design connections, which would not perform as thermal bridges. Methods of curtain walls installation are also considered in this paper.

1. Introduction

Nowadays the construction industry tends to reject the use of traditional materials for building envelopes, such as concrete, aerated concrete, and bricks. Traditional exterior walls require more time to be constructed and their installation strictly depends on the weather conditions. Cold-formed steel (CFS) is considered to be a progressive substitution of outdated materials [1].

Cold-formed steel curtain walls are considered to be a perspective technology for the exterior walls of buildings with different numbers of floors. The load-bearing structure of such a wall is a cold-formed steel frame, Figure 1. Increased thermal resistance of the CFS curtain walls is provided by an effective thermal insulation and perforated steel studs.



Figure 1. Cold-formed steel walls at the construction stage.



CFS curtain walls are a relatively new and dynamically developing construction technology. However, it is not adequately researched. Further research is required, especially at the operational stage of the building life cycle.

The aim of the study is to analyze stress-strain behavior of the cold-formed steel studs and connections between the wall and reinforced concrete slab.

To achieve the aim, the following objectives are set:

- To develop a curtain wall frame for a high-rise building and carry out a selection of cold-formed cross-sections of the stud depending on the storey height and wind load.
- To carry out a static analysis of the curtain wall frame for ultimate limit stress and serviceability limit stress
- To develop a connection between the curtain wall and reinforced concrete slab
- To carry out a numerical analysis of the stress-strain behavior of the connection
- To develop recommendations for the CFS curtain wall design

There are following problems of the research: special aspects of the multiple layer panel construction, questions considering problems of the thin-walled structures, special aspects of the connection modelling, especially bolted connections.

Comparative analysis of two types of connections was carried out in this research: the 'floor to floor' type of connection; and connection to the edge of the slab without resting on the top surface of the slab. Floor to floor connection may suppose resting on the slab fully or partly. When the wall is fully resting on the slab, the problem of the thermal bridge appears. When the wall is partly resting on the slab, the floor slab should be perfectly smooth.

There are different methods to assemble the curtain wall: by element, prefabricated etc.

Analysis of the Russian and foreign experience shows that the optimal type of connection is the connection to the edge of the slab. The third way to connect the stud frame using angles was considered in this research. Practical experience analysis showed that this connection type is less labour-consuming, Figure 2, but not sufficiently researched [2-7].

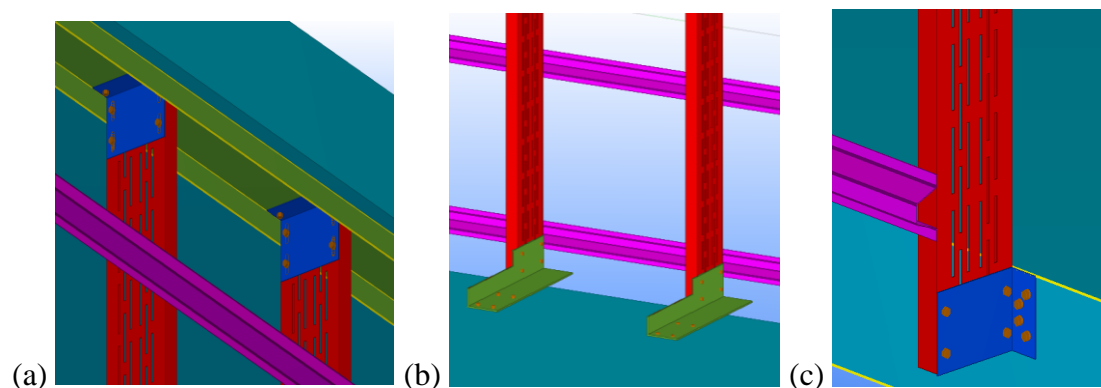


Figure 2. Types of connections between Cold-formed steel curtain wall and reinforced concrete slabs: angle and track (a), custom-shaped connection (b), angle (c).

2. Methods

Tekla Structures software was used to develop the panel structure and its connections, Figure 3. A panel with an aperture was chosen for the analysis, because exterior walls usually have window apertures. Stud spacing is determined by insulation dimensions and equals 600 mm. The hat channel trucks were applied to prevent buckling of the studs and to set cladding. Track spacing equals 500 mm.

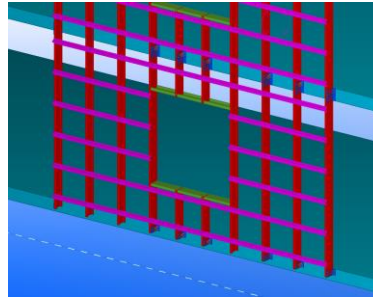


Figure 3. Curtain wall frame model Tekla Structures.

Cold-formed slotted C-profile was used for the curtain wall studs, Figure 4, which helps to reduce thermal bridges. Thickness of steel used in this research was up to 3 mm.

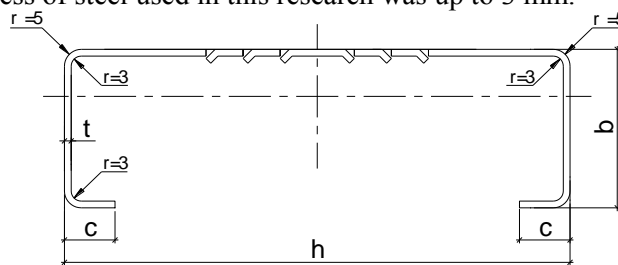


Figure 4. Slotted profile cross-section.

Use of the thin-walled slotted section requires the use of structural models based on geometrical models of the thin-walled bar for calculations. Compressed thin-walled bars have different failure modes, such as local buckling, distortional buckling, general buckling. Effective cross section is applied to take local buckling into account.

Static analysis of the studs for ultimate limit state and serviceability limit state was carried out using SCAD software. Bar finite elements were used for modeling in SCAD. Connections between studs and tracks were modeled using special SCAD elements called firm insert elements, Figure 5.

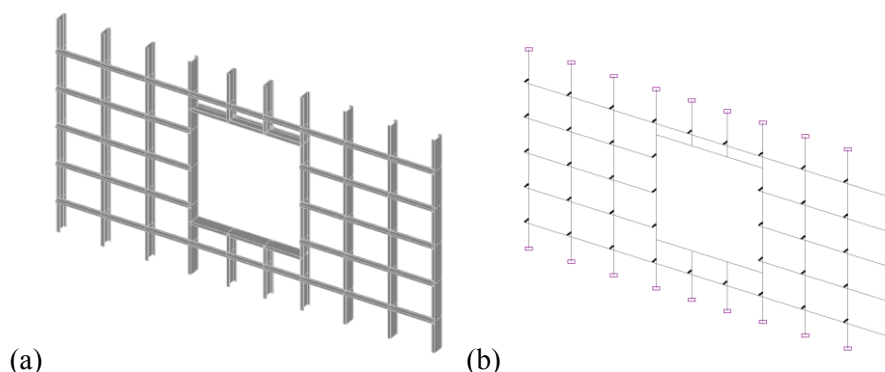


Figure 5. (a) Geometrical scheme in SCAD, (b) structural analysis scheme in SCAD.

Many researchers suggest to model cold-formed steel structures using shell members. Two models were created to verify static analysis. The first one uses bar finite elements and the second one uses shell members. The analysis showed that the bar finite elements model is sufficient to get acceptable results. Bar finite element model is less time and labour-consuming and does not reduce the accuracy of the results for the elastic stage [8, 9]. Internal forces calculated in SCAD were used for further connection analysis.

The following loads were applied to the model: self-weight of the structure, wind load and ice load for the construction stage. The pulsating component of the wind load should be taken into account when the frequency of free oscillations of the structure is less than 1.5 Hz. For the given structure a mode analysis was carried out. According to the mode analysis the frequency of free oscillations of the structure equals 11 Hz. Thus, the pulsating component of the wind load does not need to be applied to the structure. A schematic view of the wind load applying is represented Figure 6.

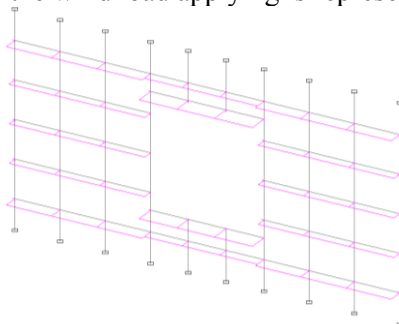


Figure 6. Wind load application in SCAD.

Different parts of the Russian Federation have absolutely different climatic parameters, because of its vast area. In particular, an unfactored wind pressure varies between 0,17 kPa and 0,85 kPa. Curtain wall panels have to meet the requirements of different wind loads. Various cross-sections were chosen depending on different wind regions due to this fact. The table 1 with different panel heights and different wind regions was created for the designers.

Wind action also adds to the load on the local parts of the facade structure. The value of this load is considerably higher than the values of average wind load. Such local parts coincide with the floor plan changes (corners, ledges etc). This study of the authors does not take into account these zones of raised wind load.

Structural analysis of the connection was carried out for the St. Petersburg region, where unfactored wind pressure equals 0.3 kPa.

Table 1. Wind load.

Unfactored wind pressure, kPa	Building height, m	Wind load, kN/m ²
0.17	100	-1.21
0.23	100	-1.636
0.30	100	-2.134
0.38	100	-2.704
0.48	100	-3.415
0.6	100	-4.269

3. Results and Discussion

The internal forces obtained in SCAD software are represented in Figure 7. Analysis of the results showed: flexural and compressive internal forces appear in the studs, but flexural internal forces prevail quantitatively; maximum internal moment appears in the stud of the window aperture and equals 3 kN·m, according to the structural analysis C-profile with 150 mm web height and 1.5 mm steel thickness was chosen for the St. Petersburg wind region (Table 2).

Table 2. Cross-sectional dimensions.

Profile	h, mm	t, mm	b, mm	r _{lt} , mm	r _t , mm	r _{et} , mm	c, mm
TC-150-1.2	150	1.2	50	3	4	5	15
TC-150-1.5	150	1.5	50	3	4	5	15
TC-150-2.0	150	2.0	50	3	4	5	15

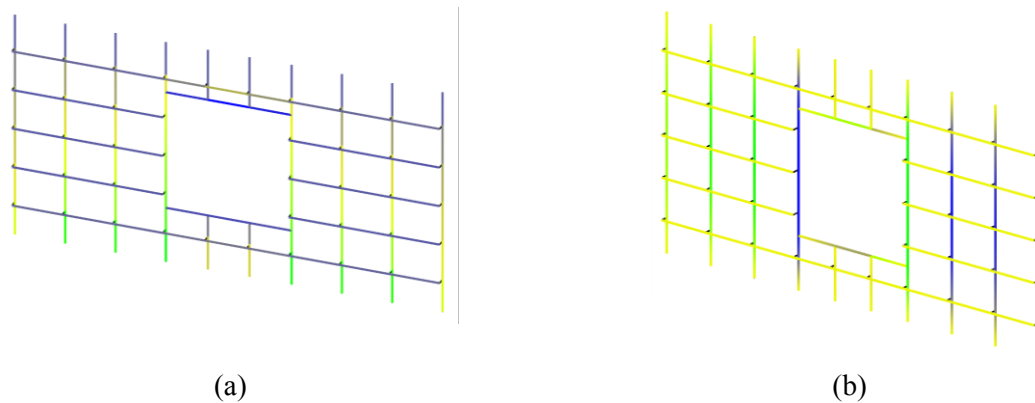


Figure 7. Statical analysis results: normal internal forces, kN (a); flexural internal forces, kNm (b).

The chosen cross section was checked for the flexural strength taking into account local stability, general stability and acceptable deformations. Calculations were carried out using reduced cross-sectional area.

The following criteria are taken into account when designing connections: stud and track strength, stiffness at the construction stage, overstressed local areas location, geometrical parameters of a building, eccentric loads presence, panel and its elements dimensions, standardization necessity, and prevailing loads. Modeling and structural analysis of the connections are usually carried out in programs based on finite element method (FEM). FEM allows solving wide range of physical problems, which are mathematically interpreted as a system of differential equations or as a variational formulation [10, 11]. This method is implemented in the ABAQUS software which was used in this study. The following stages have to be done to execute finite element modeling: to determine physical type of the task and program setting, type of finite element selection, selection of the material and its properties, geometry modeling, dividing geometry into the finite elements, set of the boundary conditions and contact parameters, calculation process and result analysis. ABAQUS has various modules to carry out all the stages mentioned above.

Module PART was used to create connection's geometry. The subject of the research was divided into two parts: angle and a fragment of the thin-walled stud (between the angle and the nearest track), Figure 8.

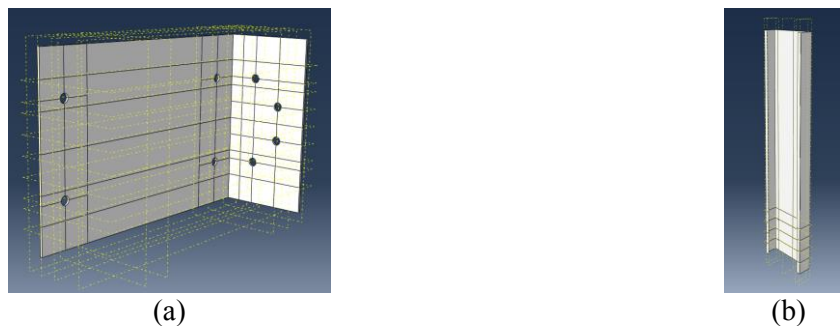


Figure 8. Members of connections in ABAQUS: (a) angle, (b) stud.

Material properties were defined using PROPERTY module. Young's modulus $E = 2,1 \cdot 10^5$ MPa, Poisson's ratio $\nu = 0,3$ and yield strength were set for the angle. Module ASSEMBLY was used to create an assembly of the parts, taking into account their mutual alignment. Module STEP was used to determine data output at steps of the calculation. Non-linear effects of big deformations were taken into account. One of the most important parameters in this module is an increment. Initial increment equals to 0.001, minimum – 1000, maximum – 1. Maximum number of steps for the calculation is

1000. Kinematic coupling boundary condition was set for the bolts imitation. This boundary condition provides cooperative movements of the apertures of the parts, Figure 10. Kinematic coupling was also set for the upper end of the stud fragment to apply flexural internal moment obtained in SCAD [12].

Finite element grid was set in the MESH module. Size of the finite elements of the angle is 4 mm, Figure 10. Size of the finite element was determined using Schwartzman method. Type of the finite element is C3D20R (general purpose quadratic brick element, with reduced integration). Problems of meshing were caused by the elements with apertures. Partition of such elements was applied to solve this problem. JOB module was used for the calculations. Parallelization was applied to make the calculation process faster. This function let the program use all processor cores.

The results of the analysis in ABAQUS are represented in Figure 9. Stress has exceeded the yield strength, the maximum deformation is 7 mm. The most optimal solution of the angle is considered to be angle with 2 mm thickness.



Figure 9. Stress, MPa (a), Deformation, mm (b).

4. Conclusion

All research objective were fulfilled:

1. Stud cross-sections were calculated depending on a wind load and storey height for a high-rise building. Recommendations: required thickness of the angle is 2 mm, when the characteristic wind load is 0.3 kPa and the storey height is 3 m, otherwise thickness of the angle has to be increased.
2. Stress-strain analysis of the connector was carried out. According to the analysis the angle should be connected to the slab at least at 4 points and to the stud at least at 4 points.
3. Only galvanized angles have to be used to connect Cold-formed curtain wall to the reinforced slab. Special filler should be located between steel and concrete to avoid electrochemical corrosion.

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