DOI:10.22337/2587-9618-2023-19-4-166-181

STATIC BEARING CAPACITY OF STEEL-PLATE COMPOSITE WALLS

Vladimir I. Travush [1], Petr D. Arleninov [2,3], Mikhail A. Desyatkin [4], Andrey N. Ivaschenko [4], Semen S. Kaprielov [2], Denis V. Konin [5], Alexey S. Krylov [5], Sergey B. Krylov [2], Igor A. Chilin [2], Andrey V. Sheinfeld [2]

[1] Gorproject, Moscow, RUSSIA
[2] JSC Research Center of Construction NIIZHB named after A.A. Gvozdev, Moscow, RUSSIA
[3] National Research Moscow State University of Civil Engineering, Moscow, RUSSIA
[4] Inforsproekt, Moscow, RUSSIA
[5] JSC Research Center of Construction TSNIISK named after V.A. Koucherenko, Moscow, RUSSIA

Abstract: The features of the behavior of steel-plate composite walls for static loads are considered. Based on the analysis of modern technical and regulatory documentation, the rationale for the chosen research topic is given. A review of the literature is performed, and the features of development are noted. A detailed description and features of the experimental structures under study and the materials used are presented. The features of the test are considered, and the test equipment is described. Analytical and numerical calculations of structures for eccentric compression have been performed. The description of the calculation complex and the used models of materials is presented; the description of numerical models, the features of their construction and calculation are given, the results of calculations are presented – stress distributions, deformations, features of cracking. The general types of experimental eccentric compression wall models are presented, the nature of the loss of bearing capacity of experimental structures is described, and a picture of destruction is presented. The analysis of the experimental data obtained and their comparison with analytical and numerical calculations are performed.

Keywords: concrete, steel, reinforced concrete, composite steel and concrete structure, steel-plate reinforcement, steel-plate composite (SC) walls, adhesion, stud

НЕСУЩАЯ СПОСОБНОСТЬ СТАЛЕЖЕЛЕЗОБЕТОННЫХ СТЕН С ЛИСТОВЫМ АРМИРОВАНИЕМ НА СТАТИЧЕСКИЕ НАГРУЗКИ

В.И. Травуш [1], П.Д. Арленинов [2,3], М.А. Десяткин [4], А.Н. Иващенко [4], С.С. Каприелов [2], Д.В. Конин [5], А.С. Крылов [5], С.Б. Крылов [2], И.А. Чилин [2], А.В. Шейнфельд [2]

[1] ЗАО «ГОРПРОЕКТ», г. Москва, РОССИЯ
[2] Научно-исследовательский, проектно-конструкторский и технологический институт бетона и железобетона (НИИЖБ) им. А.А. Гвоздева АО «НИЦ «Строительство», г. Москва, РОССИЯ
[3] ФГБОУ ВО «Национальный исследовательский Московский государственный строительный университет» (НИУ МГСУ), г. Москва, РОССИЯ
[4] ООО «Инфорспроект», г. Москва, РОССИЯ
[5] Центральный научно-исследовательский институт строительных конструкций (ЦНИИСК) имени В.А. Кучеренко АО «НИЦ «Строительство», г. Москва, РОССИЯ

Аннотация: Рассмотрены особенности работы сталежелезобетонных стен с листовым армированием при воздействии статических сжимающих нагрузок. Дано обоснование выбранной темы исследования на основе анализа современной технической и нормативной документации. Выполнен обзор литературы, отмечены особенности развития вопроса. Представлено подробное описание и особенности исследуемых экспериментальных конструкций, использованные материалы. Рассмотрены особенности испытания образцов, описано испытательное оборудование. Выполнены аналитические и численные расчеты конструкций на внецентренное сжатие. Представлено описание расчетного комплекса и использованных моделей материалов; дано описание численных моделей, особенности их построения и расчета, приведены результаты расчетов – характер распределения напряжения, деформации, особенности трещинообразования. Представлены общие виды экспериментальных моделей стен, испытанных на внецентренное сжатие, описан характер потери несущей способности экспериментальных конструкций, приведена картина разрушения. Выполнен анализ полученных экспериментальных данных, их сравнение с аналитическими и численными расчетами.

Ключевые слова: бетон, сталь, железобетон, сталежелезобетонная конструкция, листовое армирование, композитные стены с листовым армированием, сцепление, анкерное устройство

INTRODUCTION

The start of the use of composite steel and concrete structures in high-rise buildings in Russia is recorded in the 50s of the 20th century. The history of composite steel and concrete structures in Russia started with the construction of «Stalin's skyscrapers». The Eurasia skyscraper in Moscow City and the Lakhta Center in St. Petersburg are the latest examples of composite steel and concrete structures in Russia. The use of composite structures in Europe, Asia and the USA has long been known, and also popular in high-rise buildings and bridge construction.

The listed buildings are examples of «classic» composite steel and concrete structures. At the end of the 20th century, another type of composite steel and concrete structure was developed. These are steel-plate composite (SC) structures. They are used in the construction of nuclear power plants in Japan, China, South Korea, the USA and Russia. Initially, the steel-plates were used only as an external formwork, which is not involved in structural strength calculations.

Significant research on the behavior of SC walls for various loading conditions has been performed in Japan [1, 2], China [3…5], and South Korea [6…11]. The research in Japan and South Korea has been the basis for design standards for steel-plate composite construction in Japan (JEAG (2005), Technical Guidelines for Seismic Design of Nuclear Power Plants, JEA (Japan Electric Association)) and South Korea (KSSC (2010), Specification for Safety-Related Steel Plate Concrete Structures for Nuclear Facilities, KEPIC-SNG, Board of KEPIC Policy, Structural Committee, Korea Electric Association).

In the United States, extensive research has been conducted over the past decade to evaluate the behavior of steel-plate composite walls and connections and to develop design standards, such as the AISC Specification for Safety-Related Steel Structures for Nuclear Facilities (AISC, 2015). Some scientific research is given below [33].

The out-of-plane shear behavior of steel-plate composite walls was evaluated by Varma et al. [12], Sener and Varma [13], and Sener et al. [14]. The out-of-plane flexure behavior of SC walls was analyzed by Sener et al. [15]. The in-plane behavior and design of SC walls was evaluated by Varma et al. [16], Seo et al. [17], and Kurt et al. [18]. The local buckling behavior of steel face plates in steel-plate composite walls and the composite action between steel plates and concrete infill was evaluated by Varma et al. [19], Zhang [20], Zhang et al. [21], and Bhardwaj and Varma [22]. The behavior of steel-plate composite walls subjected to combined in-plane forces and out-of-plane flexure was presented by Varma et al. [23, 24]. The behavior, design and shear strength of SC wall-towall T-joints and L-joints were evaluated by Seo et al. [25], Seo [26], and Seo and Varma [27]. The design and detailing of faceplates, steel anchors and ties of SC walls to prevent local buckling, interfacial shear failure, and section delamination failure were presented in Bhardwaj et al. [28]. This paper also presented the design of steel anchors and ties to account for the effect of combined shear forces [33]. The lateral load capacity of SC walls with boundary elements was evaluated by Booth et al. [29]. The lateral load capacity of SC walls without boundary elements was evaluated by Epackachi et al. [30], Kurt et al. [31], and Bhardwaj et al. [32, 33].

SC construction has numerous advantages over reinforced concrete construction:

- increased resistance to radiation, explosions and flying debris;
- increased resistance to loads from the plane - bending and shear;
- transferring most of the work to factory conditions;
- reduction of work on the construction site (no formwork, no reinforcing frame and no maintenance of concrete);
- no need to apply waterproofing due to the tightness of the structure;
- modular assembly and, consequently, a reduction in the time of work on the construction site;
- improving the quality of construction work.

In Russia, steel-plate composite structures were used in the construction of nuclear power plants. For the development of the construction industry in Russia, including high-rise construction, with the use of modern technologies, a series of experiments of steel-plate composite walls was planned. The results of this experiment will be used as the basis for numerical studies of composite steel and concrete constructions in a nonlinear setting contact interaction simulation. The obtained experimental data are the necessary stage of work for further verification of calculation methods.

The purpose of the work is to test models of steel-plate composite walls for experimental and theoretical justification of their use in high-rise building structures.

Tasks of the work:

• analysis of the available literature on the research topic;

• make work programs for experimental research;

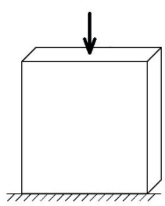
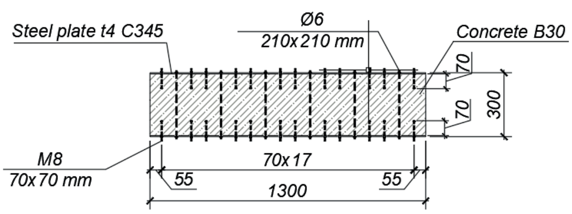
• experimental research;

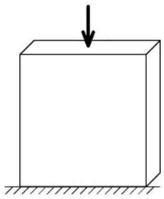
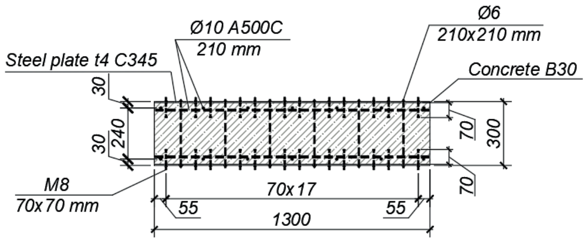
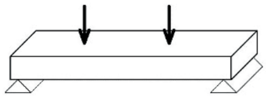
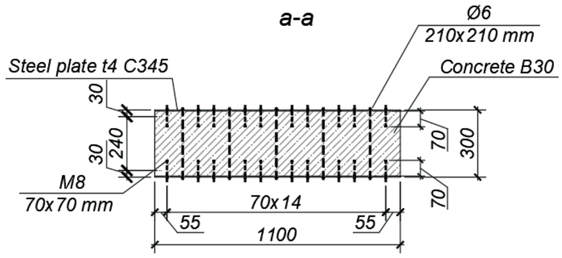
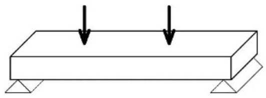
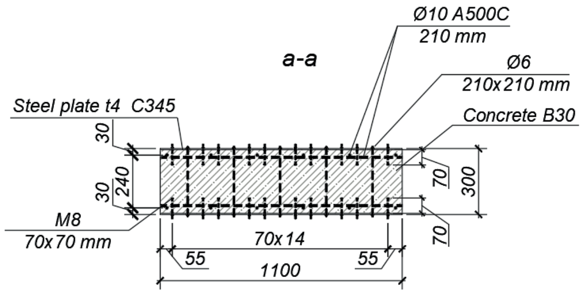
• numerical modeling of structures in specialized research software systems, comparison with test results.

METHODS

Within the research 12 models of steel-plate composite walls with rectangular cross-section 1300 (1100) x 300mm and a length 3000 mm have been tested. Six models have been tested for eccentric compression, and six models have been tested for bending. The models characteristics (cross-section type, construction materials) are stated in Table 1.

<u>Table 1.</u> The Models Characteristics

Group of models	Number of models in the group	Concrete compression breaking strength class	Diagram of load application to the models	Cross-section
1.1	3	B30		

1.2	3	B30		
2.1	3	B30		
2.2	3	B30		

Steel headed stud anchors (was modeled by bolts) were installed on the inside of all the steel plates (Figure 1). The steel plates were connected by tie bars. Models 1.1, 2.1 did not have bar reinforcement of concrete, models 2.1, 2.2 were reinforced with bars.

Preparation of the models for the experiment has been carried out in the following sequence: steel plates have been manufactured and frame reinforcement has been tied (Figure 1); resistive-strain sensors have been installed on the pretreated steel surface and protected (Figure 2); concrete has been poured and resistive-strain sensors have been attached to the steel-plates. The sensors location schemes are shown in Figure 3.

Figure 1. Steel plates and frame reinforcement

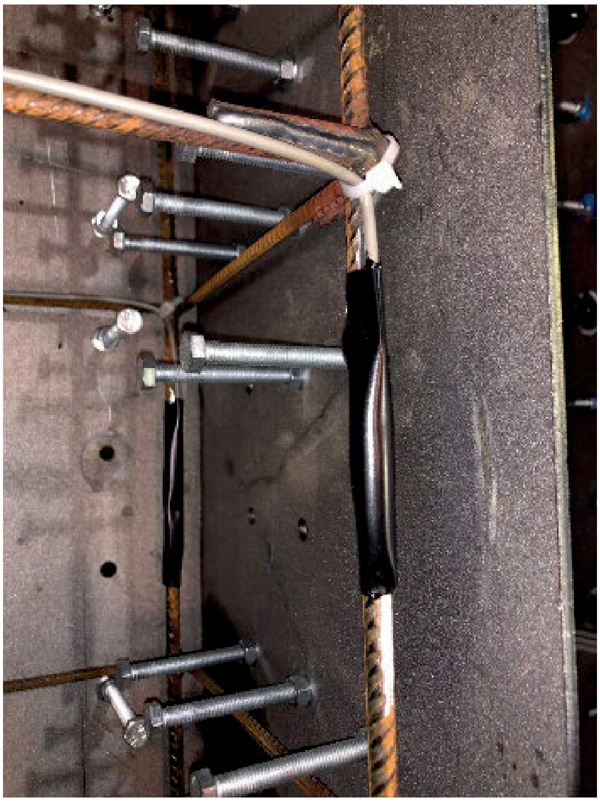


Figure 2. Resistive-strain sensors. Installation and protection

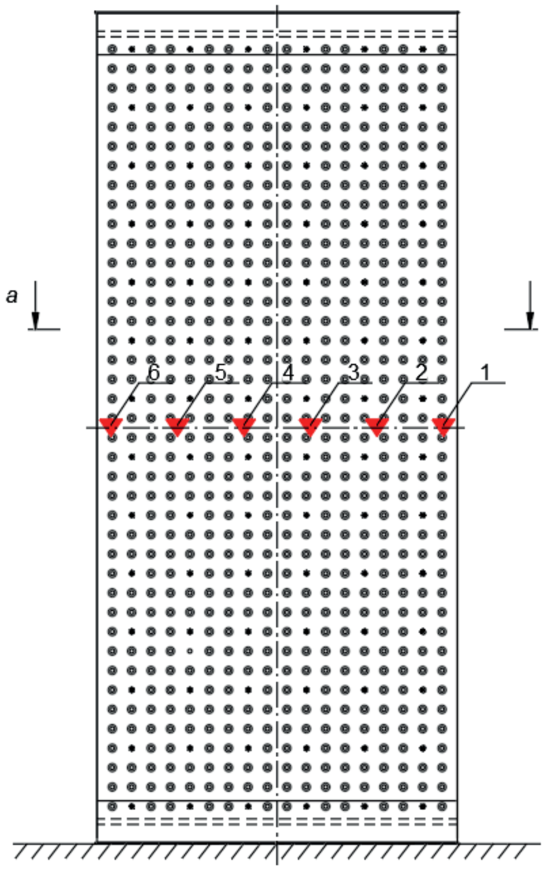


Figure 3b. The sensors location schemes for models 1.1, 2.1 (side view)

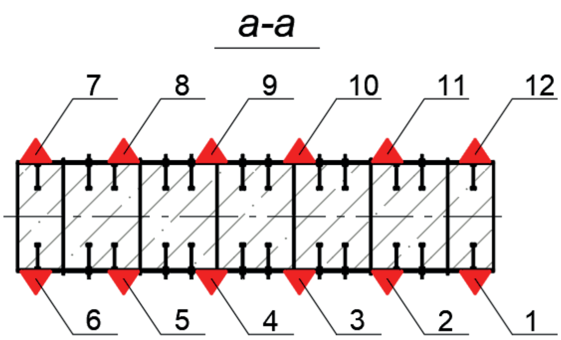


Figure 3a. The sensors location schemes for models 1.1, 2.1 (the section in the center of the height)

Models supports were hinge. A typical view of models tested for bending is shown in Figure 4. A typical view of models tested for eccentric compression is shown in Figure 5.

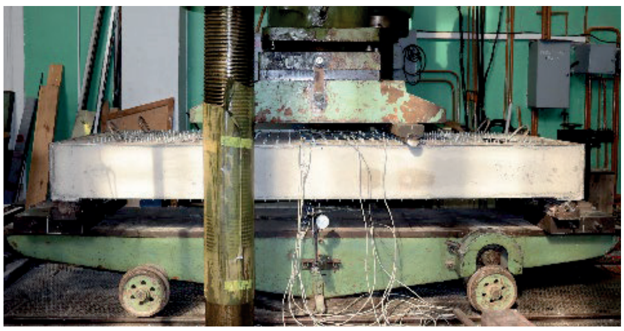


Figure 4. Typical view of models tested for bending

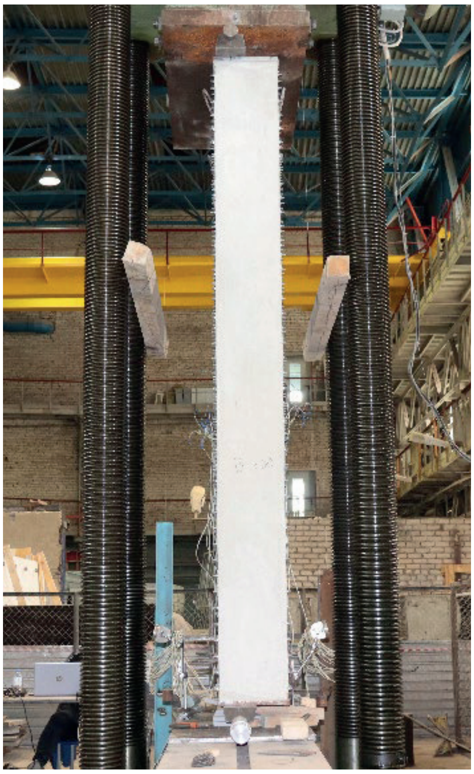


Figure 5. Typical view of models tested for eccentric compression

Very important characteristic of steel-plate composite walls is rigidity, also long-term rigidity. Elastic and plastic deformations due to creep and shrinkage depend on long-term rigidity. The standard formulas of structural mechanics make it possible to determine the elastic stiffness characteristics of a composite steel and concrete element. Determining the long-term modulus of elasticity remains an incompletely solved problem. Based on the best practices in terms of model compliance, during the transition from actual structural elements to small samples, special steel-reinforced concrete samples were prepared for testing to determine the shrinkage and creep of concrete. An article on these tests is being prepared by the authors and will be published soon.

RESULTS AND DISCUSSION

According to the test results, the types of destruction of the models were obtained and the maximum bearing capacity was determined.

The destruction of eccentrically compressed models (models 1.1, 1.2) was on compressed concrete, characterized by limit stress followed by concrete chipping and steel sheet crumpling. The destroyed model is shown in Figure 6. The destruction of the bent models (models 2.1, 2.2) was due to the shear force, characterized by the formation and opening of an inclined crack - from the load transfer zone to the support. The destroyed model is shown in Figure 7.

The results of the experiment showed the combined work of steel plates with concrete at all stages of loading up to the destruction of models.

Figure 6. Typical view of destruction of models tested for eccentric compression

Figure 7a. Typical view of destruction of models tested for bending

Figure 7b. Typical view of destruction of models tested for bending

Diagrams of vertical deformations from the load are obtained. Diagrams for models 1.1, 1.2 are shown in Figure 8, for models 2.1, 2.2 are shown in Figure 9.

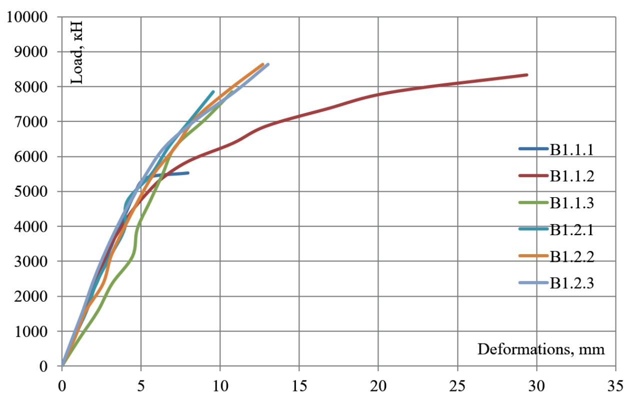


Figure 8. Load-deformation diagrams for models 1.1, 1.2

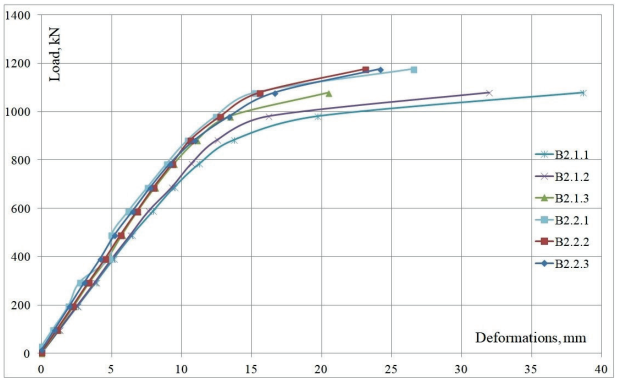


Figure 9. Load-deformation diagrams for models 2.1, 2.2

Diagrams for stress in faceplates are shown in the Figures 10, 11 for models 1.1, 1.2 and 2.1, 2.2 respectively.

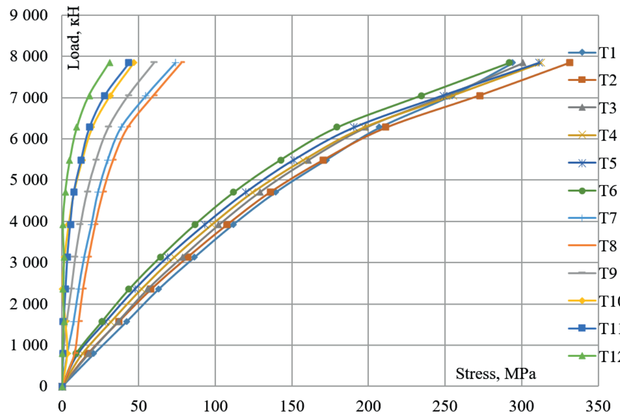


Figure 10. Stress-load diagrams for model faceplates (for model 1.2.1 for example)

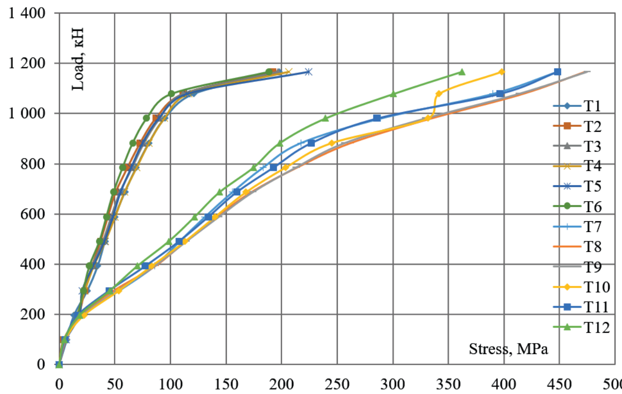


Figure 11. Stress-load diagrams for modes faceplates (for model 2.1.2 for example)

Diagrams of stress distribution according to models are obtained. Diagrams for models 2.1, 2.2 (bending tests) are shown in Figure 12.

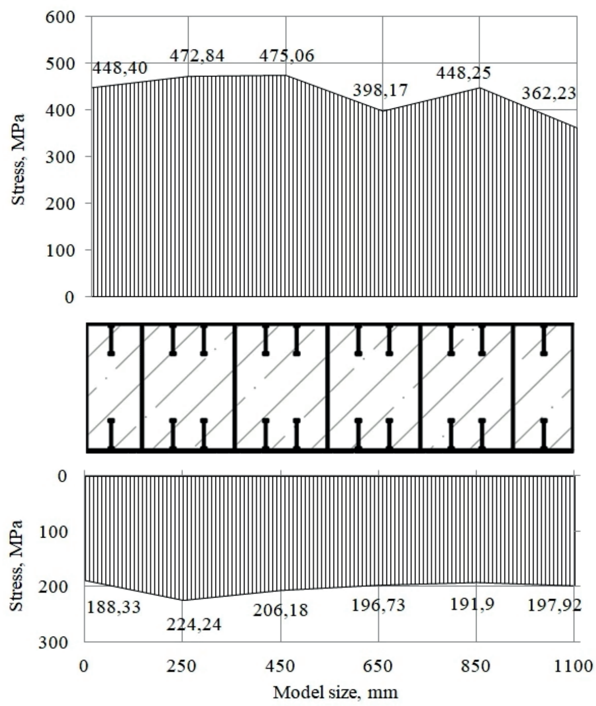


Figure 12. Diagrams of stress distribution for model faceplates (bending tests, models 2.1, 2.2)

For a detailed study of the features of the structures, numerical modeling was performed in the ATENA software package (developed by Červenka Consulting).

The calculations of the models are performed by the finite element method. The software package has an extensive database of various types of finite elements and material models. Numerical models are developed taking into account the recommendations of the software using 1D (bar reinforcement) and volume 3D Solid Elements (concrete and steel plate) finite elements. The dimensions of the finite element grid, the calculation parameters were selected and set based on the solution of test problems, in the necessary places the grid had a smaller size of the FE. The number of load application steps was taken 20...50. The conditions of support and loading of the models are set in accordance with similar parameters in the experiments. The parameters of reinforcement and concrete are described by actual diagrams of deformation of materials.

The calculation models are shown in Figures 13, 14.

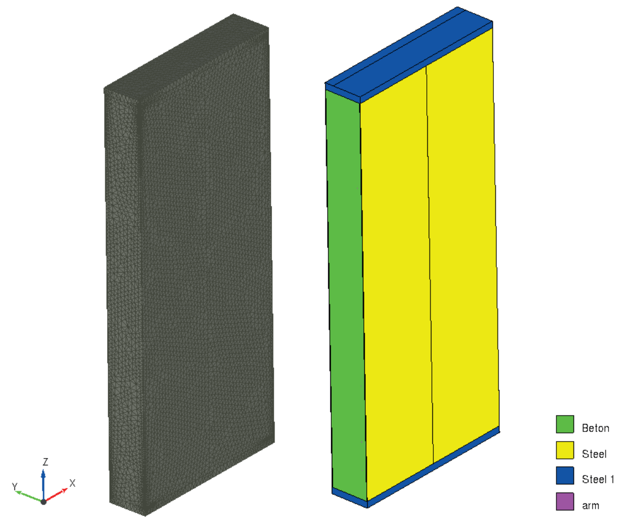


Figure 13. Calculation models 1.1, 1.2 (eccentric compression tests)

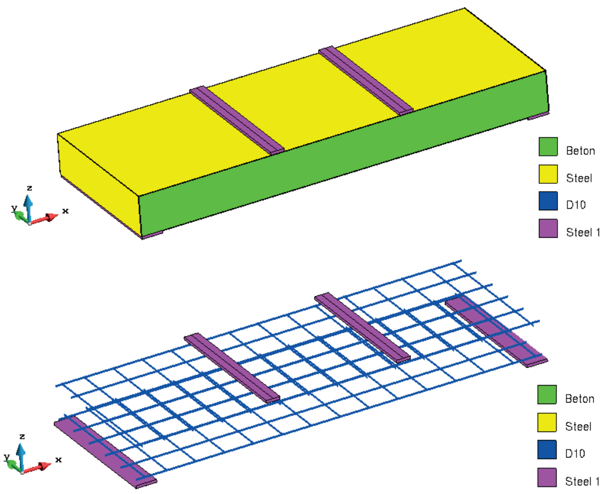


Figure 14. Calculation models 1.1, 1.2 (bending tests)

The calculation results are shown in the Figures 15…18. The width of the opening and the location of cracks in the structure are in good agreement with the experimental results (Figure 15). The analysis of the results of numerical calculations showed that the stresses in steel plates and concrete have limiting values, which corresponds to experimental data (Figure 16, 17).

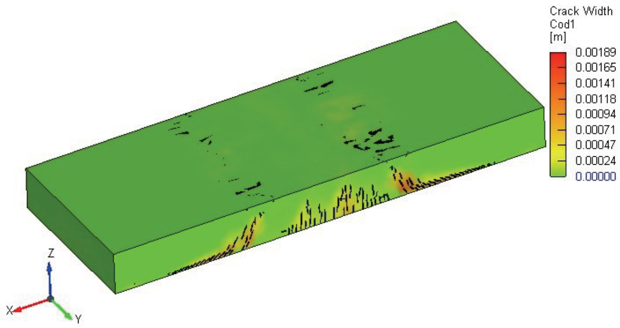


Figure 15. Calculation results. Crack opening width

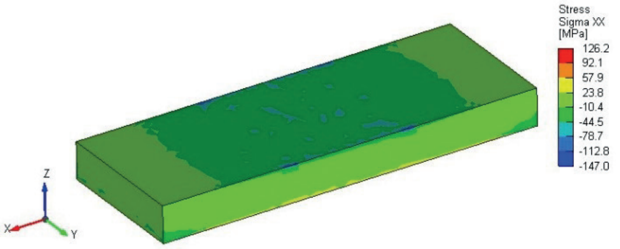


Figure 16. Calculation results. Stress in concrete

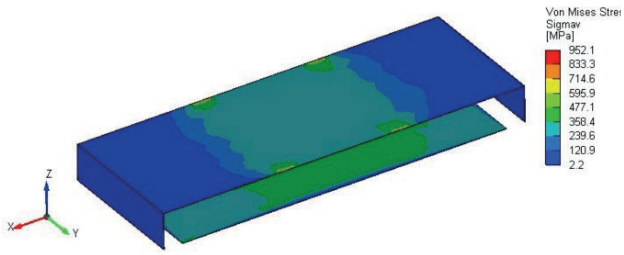


Figure 17. Calculation results. Stress in faceplates

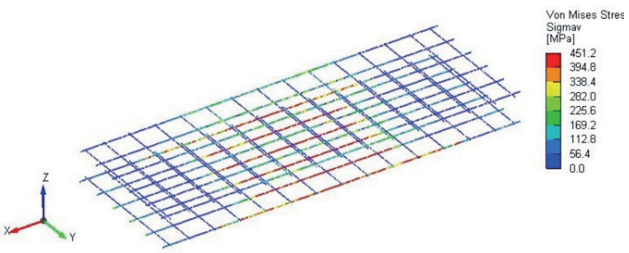


Figure 18. Calculation results. Stress in bar reinforcement

CONCLUSION

1. In this paper the issues of the development of composite steel and concrete structures have been considered. The review of experimental and theoretical studies of steel-plate composite structures is carried out.
2. According to the experimental research program, 12 models of steel-plate composite structures were tested for eccentric compression and bending. The analysis and processing of experimental data has been performed.
3. Numerical models have been constructed to study the features of the stress-strain state of steel-plate composite structures. Based on the calculations performed, the values of the bearing capacity of structures were obtained; the nature of cracking and deformation of steel-plate composite structures under eccentric compression and bending was assessed. The results of numerical studies allow for a more detailed assessment of the stress-strain state of structures.
4. The data of experimental, numerical and theoretical studies are analyzed. The data obtained indicate that the numerical and experimental models correspond. This allows us to extend the results of numerical calculations to a large list of models with different sizes and made of different classes of concrete. Based on the tests, it is planned to develop an analytical methodology for calculating steel-plate composite walls, taking into account possible various design solutions.
5. According to the results of this work, it was noted that the type of structures under study is technologically advanced and has great potential. It is necessary to continue research to form a complete picture of the actual behavior of structures for the development of calculation methods.
6. The data in this article are a small part of a large experiment. A large series of experimental work on the study of steel-plate composite structures is planned. Various parameters were studied on a large group of models under various conditions of support and loading. Studies of elastic and plastic deformations due to creep and shrinkage are also carried out. At the moment, most of the experimental studies have been completed,

and data processing is in progress. An article on these tests with detailed results is being prepared by the authors and will be published soon.

ACKNOWLEDGEMENT

The authors of the article thank their colleagues for their help in experimental work:

- Daria Morozova, Ksenia Morozova, Dmitry Gavrilov, Anastasia Zhdanova, Maria Voropaeva (Research Institute of Building Constructions (TSNIISK) Named After V. A. Koucherenko JSC "Research center of Construction") – preparation of experimental models (installation of strain gauges), analysis and processing of experimental results;
- Artur Dottuev, Zaur Abrekov, Nurik Aliyev (Research Institute of Building Constructions (TSNIISK) Named After V. A. Koucherenko JSC "Research center of Construction") – experimental research, preparation of strain measurements, strain gauge processing

REFERENCES

1. **Takeuchi M., Narikawa M., Matsuo I., Hara, K. and Usami S**. (1998) Study on a Concrete Filled Structure for Nuclear Power Plants. *Nuclear Engineering and Design*, vol. 179, no 2, pp. 209–223.
2. **Takeuchi M., Fujita F., Funakoshi A., Shohara R., Akira S. and Matsumoto R.** (1999) Experimental Study on Steel Plate Reinforced Concrete Structure, Part 2: Response of SC Members Subjected to Out-of-Plane Load (Outline of the Experimental Program and the Results). *Proceedings of the Annual Conference of Architectural Institute of Japan, (in Japanese)*, pp. 1.037–1.038.
3. **Song X., Chu M., Ge H. and Wang H.** (2014) A Failure Criterion for Steel-Concrete Composite Walls. *Sustainable Development of Critical Infrastructure, ASCE*, pp. 324–331.
4. **Leng Y.-B., Song X.-B., Chu M. and Ge H.-H.** (2015) Experimental Study and Theoretical Analysis of Resistance of Steel-Concrete-Steel Sandwich Beams. *Journal of Structural Engineering, ASCE,* vol. 141, no. 2.
5. **Leng Y.-B., Song X.-B. and Wang H.-L.** (2015) Failure Mechanism and Shear Strength of Steel-Concrete-Steel Sandwich Deep Beams, *Journal of Constructional Steel Research*, vol. 106, pp. 89–98.
6. **Moon I.H., Kim S.M., Kim W.B. and Kim W.K.** (2007) The Use of Steel Plate Concrete for Structural Module of NPP Structures, *Journal of the Korean Society of Steel Construction (in Korean)*, vol. 19, no. 2, pp 740–745.
7. **Moon I.H., Kim T.Y. and You S.T.** (2008) Nuclear Power Plant Structure and SC Structure Design, *Journal of the Korean Society of Steel Construction (in Korean)*, vol. 20, no. 2, pp. 14–23.
8. **Kim W.B. and Kim W.K.** (2008) Status and Background in Developing SC Structure Specifications for Nuclear Power Plants, *Journal of the Korean Society of Steel Construction (in Korean)*, vol. 20, no. 2, pp. 9–13.
9. **Lee U.W., Kim K.K., Mun T.Y. and Sun W.S.** (2008) Nuclear Power Plant Construction and SC Structures, *Journal of the Korean Society of Steel Construction (in Korean)*, vol. 20, no. 2.
10. **Lee S.J., Choi B.J. and Kim T.K.** (2009) An Experimental Study on the Behavior of Steel Plate Concrete Wall with Vertical Ribs, *Journal of the Korean Society of Steel Construction (in Korean)*, vol. 21, no. 3, pp. 277–287.
11. **Hong S., Kim W., Lee K., Hong N.K. and Lee D.** (2009) Out-of-Plane Shear Strength of Steel Plate Concrete Walls Dependent on Bond Behavior, *Transactions of the 20th International Conference on Structural Mechanics in Reactor Technology*, SMiRT-20, Div-6: Paper 1,855, Espoo, Finland,

IASMIRT, North Carolina State University, Raleigh, NC, pp. 1–10.

12. **Varma A.H., Sener K.C., Zhang K., Coogler K. and Malushte S.R.** (2011) *Out-of-Plane Shear Behavior of SC Composite Structures*, Transactions of the 21st International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-21, New Delhi, India, IASMART, North Carolina State University, Raleigh, NC.
13. **Sener K.C. and Varma A.H.** (2014) Steel-Plate Composite Walls: Experimental Database and Design for Out-of-Plane Shear, *Journal of Constructional Steel Research*, vol. 100, pp. 197–210.
14. **Sener K.C., Varma A.H. and Seo J.** (2016) Experimental and Numerical Investigation of the Shear Behavior of Steel-Plate Composite (SC) Beams without Shear Reinforcement, *Engineering Structures*, vol. 127, pp. 495–509.
15. **Sener K.C., Varma A.H., Booth P.N. and Fujimoto R.** (2015) Seismic Behavior of a Containment Internal Structure Consisting of Composite SC Walls, *Nuclear Engineering and Design*, vol. 295, pp. 804–816.
16. **Varma A.H., Zhang K., Chi H., Booth P.N. and Baker T.** (2011) *In-Plane Shear Behavior of SC Walls: Theory vs. Experiment*, Transactions of the 21st International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-21, Div. X, Paper 761, New Delhi, India, IASMART, North Carolina State University, Raleigh, NC.
17. **Seo J., Varma A.H., Sener K. and Ayhan D.** (2016) Steel-Plate Composite (SC) Walls: In-Plane Shear Behavior, Database, and Design, *Journal of Constructional Steel Research*, vol. 119, pp. 202–215.
18. **Kurt E.G., Varma A.H., Booth P.N. and Whittaker A.** (2016) In-plane Behavior and Design of Rectangular SC Wall Piers Without Boundary Elements, *Journal of Structural Engineering, ASCE*, vol. 142, no. 6.
19. **Varma A.H., Zhang K. and Malushte S.R.** (2013), *Local Buckling of SC Composite Walls at Ambient and Elevated Temperatures*, Transactions of the 22nd International Conference on Structural Mechanics in Reactor Technology, SMiRT-22, San Francisco, CA, IASMART, North Carolina State University, Raleigh, NC.
20. **Zhang K.** (2014) Axial Compression Behavior and Partial Composite Action of SC Walls in Safety-Related Nuclear Facilities, Ph.D. Dissertation, Purdue University, West Lafayette, IN.
21. **Zhang K., Varma A.H., Malushte S.R. and Gallocher S.** (2014) Effect of Shear Connectors on Local Buckling and Composite Action in Steel Concrete Composite Walls, *Journal of Nuclear Engineering and Design, Special Issue on SmiRT-21 Conference*, vol. 269, pp. 231–239.
22. **Bhardwaj S.R. and Varma A.H.** (2016) Effect of Imperfections on the Compression Behavior of SC Walls, *Proceedings of the Annual Stability Conference, Structural Stability Research Council*, Orlando, FL, April 12–15.
23. **Varma A.H., Malushte S.R., Sener K. and Lai Z.** (2011), *Steel-Plate Composite Walls for Safety Related Nuclear Facilities: Design for Combined In-Plane and Out-of-Plane Demands*, Transactions of the 21st International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-21, Paper ID 760, New Delhi, India, IASMART, North Carolina State University, Raleigh, NC.
24. **Varma A.H., Malushte S.R., Sener K.C. and Lai Z.** (2014) Steel-Plate Composite (SC) Walls for Safety Related Nuclear Facilities: Design for In-Plane Forces and Out-of-Plane Moments, *Nuclear Engineering and Design, Special Issue on SMiRT-21 Conference*, vol. 269, pp. 240–249.
25. **Seo J., Varma A.H. and Winkler D.** (2013) *Preliminary Investigations of the Joint Shear Strength of SC Wallto-Wall T-Joints*, Transactions of the 22nd International

Association for Structural Mechanics in Reactor Technology Conference, SMiRT-22, San Francisco, CA, IASMART, North Carolina State University, Raleigh, NC, pp. 1–10.
26. **Seo J.** (2014) Design of Steel Concrete Composite Wallto-Wall Joints for Safety-Related Nuclear Facilities, Ph.D. Dissertation, Purdue University, West Lafayette, IN.
27. **Seo J. and Varma A.H.** (2015) *Behaviour and Design of Corner or L-Joints in SC Walls*, Transactions of the 23rd International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-23, Paper ID 695, Manchester, UK, IASMIRT, North Carolina State University, Raleigh, NC.
28. **Bhardwaj S.R., Varma, A.H. and Malushte S.R.** (2017) Minimum Requirements and Section Detailing Provisions for Steel-Plate Composite (SC) Walls in Nuclear Power Plants, *Engineering Journal*, *AISC*, vol. 54, no. 2.
29. **Booth P., Varma A.H. and Seo J.** (2015), *Lateral Load Capacity of Steel Plate Composite Wall Structures*, Transactions of the 23rd International Conference on Structural Mechanics in Reactor Technology, SMiRT-23, Paper ID 791, Manchester, UK, IASMIRT, North Carolina State University, Raleigh, NC, pp. 1–10.
30. **Epackachi S., Nguyen N., Kurt E., Whittaker A. and Varma, A.** (2015) In-Plane Seismic Behavior of Rectangular Steel-Plate Composite Wall Piers, *Journal of Structural Engineering, ASCE*, vol. 141, no. 7.
31. **Kurt E.G., Varma A.H., Booth P.N. and Whittaker A.** (2016) In-plane Behavior and Design of Rectangular SC Wall Piers Without Boundary Elements, Journal of Structural Engineering, ASCE, vol. 142, no. 6.
32. **Bhardwaj S.R., Kurt E.G., Terranova B., Varma A.H., Whittaker A.S. and Orbovic, N.** (2015) Preliminary Investigation of the Effects of Out-of-Plane Loading on the In-Plane Behavior of SC Walls, *Transactions of the 23rd Structural Mechanics in Reactor Technology*, SMiRT-23, Paper ID 712, Manchester, UK, IASMIRT, North Carolina State University, Raleigh, NC, pp. 1–10.
33. AISC Design Guide 32: Modular Steel-Plate Composite Walls for Safety-Related Nuclear Facilities. American Institute of Steel Construction.

СПИСОК ЛИТЕРАТУРЫ

1. **Takeuchi M., Narikawa M., Matsuo I., Hara, K. and Usami S**. // Study on a Concrete Filled Structure for Nuclear Power Plants. Nuclear Engineering and Design, 1998, Vol. 179, no 2, pp. 209–223.
2. **Takeuchi M., Fujita F., Funakoshi A., Shohara R., Akira S. and Matsumoto R.** Experimental Study on Steel Plate Reinforced Concrete Structure, Part 2: Response of SC Members Subjected to Out-of-Plane Load (Outline of the Experimental Program and the Results) // Proceedings of the Annual Conference of Architectural Institute of Japan, Japan, 1999, pp. 1.037–1.038.
3. **Song X., Chu M., Ge H. and Wang H. A**. Failure Criterion for Steel-Concrete Composite Walls // Sustainable Development of Critical Infrastructure, ASCE, 2014, pp. 324–331.
4. **Leng Y.-B., Song X.-B., Chu M. and Ge H.-H.** Experimental Study and Theoretical Analysis of Resistance of Steel-Concrete-Steel Sandwich Beams // Journal of Structural Engineering, ASCE, 2015, Vol. 141, No. 2.
5. **Leng Y.-B., Song X.-B. and Wang H.-L.** Failure Mechanism and Shear Strength of Steel-Concrete-Steel Sandwich Deep Beams // Journal of Constructional Steel Research, 2015, Vol. 106, pp. 89–98.
6. **Moon I.H., Kim S.M., Kim W.B. and Kim W.K.** The Use of Steel Plate Concrete for Structural Module of NPP Structures, // Journal of the Korean Society of Steel

Construction (in Korean), 2007, Vol. 19, No. 2, pp 740–745.

7. **Moon I.H., Kim T.Y. and You S.T.** Nuclear Power Plant Structure and SC Structure Design // Journal of the Korean Society of Steel Construction (in Korean), 2008, Vol. 20, No. 2, pp. 14–23.
8. **Kim W.B. and Kim W.K.** Status and Background in Developing SC Structure Specifications for Nuclear Power Plants // Journal of the Korean Society of Steel Construction (in Korean), 2008, Vol. 20, No. 2, pp. 9–13.
9. **Lee U.W., Kim K.K., Mun T.Y. and Sun W.S.** Nuclear Power Plant Construction and SC Structures // Journal of the Korean Society of Steel Construction (in Korean), 2008, Vol. 20, No. 2.
10. **Lee S.J., Choi B.J. and Kim T.K.** An Experimental Study on the Behavior of Steel Plate Concrete Wall with Vertical Ribs // Journal of the Korean Society of Steel Construction (in Korean), 2009, Vol. 21, No. 3, pp. 277–287.
11. **Hong S., Kim W., Lee K., Hong N.K. and Lee D.** Out-of-Plane Shear Strength of Steel Plate Concrete Walls Dependent on Bond Behavior // Transactions of the 20th International Conference on Structural Mechanics in Reactor Technology, SMiRT-20, Div-6: Paper 1,855, Espoo, Finland, IASMIRT, North Carolina State University, Raleigh, NC, 2009, pp. 1–10.
12. **Varma A.H., Sener K.C., Zhang K., Coogler K. and Malushte S.R.** Out-of-Plane Shear Behavior of SC Composite Structures // Transactions of the 21st International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-21, New Delhi, India, IASMART, North Carolina State University, Raleigh, NC, 2009.
13. **Sener K.C. and Varma A.H.** Steel-Plate Composite Walls: Experimental Database and Design for Out-of-Plane Shear // Journal of Constructional Steel Research, 2014, Vol. 100, pp. 197–210.
14. **Sener K.C., Varma A.H. and Seo J.** Experimental and Numerical Investigation of the Shear Behavior of Steel-Plate Composite (SC) Beams without Shear Reinforcement // Engineering Structures, 2016, Vol. 127, pp. 495–509.
15. **Sener K.C., Varma A.H., Booth P.N. and Fujimoto R.** Seismic Behavior of a Containment Internal Structure Consisting of Composite SC Walls // Nuclear Engineering and Design, 2015, Vol. 295, pp. 804–816.
16. **Varma A.H., Zhang K., Chi H., Booth P.N. and Baker T.** In-Plane Shear Behavior of SC Walls: Theory vs. Experiment, Transactions of the 21st International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-21, Div. X, Paper 761, New Delhi, India, IASMART, North Carolina State University, Raleigh, NC, 2011.
17. **Seo J., Varma A.H., Sener K. and Ayhan D.** Steel-Plate Composite (SC) Walls: In-Plane Shear Behavior, Database, and Design // Journal of Constructional Steel Research, 2016, Vol. 119, pp. 202–215.
18. **Kurt E.G., Varma A.H., Booth P.N. and Whittaker A.** In-plane Behavior and Design of Rectangular SC Wall Piers Without Boundary Elements // Journal of Structural Engineering, ASCE, 2016, Vol. 142, No. 6.
19. **Varma A.H., Zhang K. and Malushte S.R.** Local Buckling of SC Composite Walls at Ambient and Elevated Temperatures, Transactions of the 22nd International Conference on Structural Mechanics in Reactor Technology, SMiRT-22, San Francisco, CA, IASMART, North Carolina State University, Raleigh, NC, 2013.
20. **Zhang K.** Axial Compression Behavior and Partial Composite Action of SC Walls in Safety-Related Nuclear Facilities, Ph.D. Dissertation, Purdue University, West Lafayette, IN, 2014.
21. **Zhang K., Varma A.H., Malushte S.R. and Gallocher S.** Effect of Shear Connectors on Local Buckling and

Composite Action in Steel Concrete Composite Walls // Journal of Nuclear Engineering and Design, Special Issue on SmiRT-21 Conference, 2014, Vol. 269, pp. 231–239.

22. **Bhardwaj S.R. and Varma A.H.** Effect of Imperfections on the Compression Behavior of SC Walls, Proceedings of the Annual Stability Conference, Structural Stability Research Council, Orlando, FL, April 12–15, 2016.
23. **Varma A.H., Malushte S.R., Sener K. and Lai Z.** Steel-Plate Composite Walls for Safety Related Nuclear Facilities: Design for Combined In-Plane and Out-of-Plane Demands, Transactions of the 21st International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-21, Paper ID 760, New Delhi, India, IASMART, North Carolina State University, Raleigh, NC, 2011.
24. **Varma A.H., Malushte S.R., Sener K.C. and Lai Z.** Steel-Plate Composite (SC) Walls for Safety Related Nuclear Facilities: Design for In-Plane Forces and Out-of-Plane Moments // Nuclear Engineering and Design, Special Issue on SMiRT-21 Conference, 2014, Vol. 269, pp. 240–249.
25. **Seo J., Varma A.H. and Winkler D.** Preliminary Investigations of the Joint Shear Strength of SC Wallto-Wall T-Joints, Transactions of the 22nd International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-22, San Francisco, CA, IASMART, North Carolina State University, Raleigh, NC, 2013, pp. 1–10.
26. **Seo J.** Design of Steel Concrete Composite Wallto-Wall Joints for Safety-Related Nuclear Facilities, Ph.D. Dissertation, Purdue University, West Lafayette, IN, 2014.
27. **Seo J. and Varma A.H.** Behaviour and Design of Corner or L-Joints in SC Walls, Transactions of the 23rd International Association for Structural Mechanics in Reactor Technology Conference, SMiRT-23, Paper ID 695, Manchester, UK, IASMIRT, North Carolina State University, Raleigh, NC, 2015.
28. **Bhardwaj S.R., Varma, A.H. and Malushte S.R.** Minimum Requirements and Section Detailing Provisions for Steel-Plate Composite (SC) Walls in Nuclear Power Plants // Engineering Journal, AISC, 2017, Vol. 54, No. 2.
29. **Booth P., Varma A.H. and Seo J.** Lateral Load Capacity of Steel Plate Composite Wall Structures, Transactions of the 23rd International Conference on Structural Mechanics in Reactor Technology, SMiRT-23, Paper ID 791, Manchester, UK, IASMIRT, North Carolina State University, Raleigh, NC, 2015, pp. 1–10.
30. **Epackachi S., Nguyen N., Kurt E., Whittaker A. and Varma, A.** In-Plane Seismic Behavior of Rectangular Steel-Plate Composite Wall Piers, Journal of Structural Engineering, ASCE, 2015, Vol. 141, No. 7.
31. **Kurt E.G., Varma A.H., Booth P.N. and Whittaker A.** In-plane Behavior and Design of Rectangular SC Wall Piers Without Boundary Elements, Journal of Structural Engineering, ASCE, 2016, Vol. 142, No. 6.
32. **Bhardwaj S.R., Kurt E.G., Terranova B., Varma A.H., Whittaker A.S. and Orbovic, N.** Preliminary Investigation of the Effects of Out-of-Plane Loading on the In-Plane Behavior of SC Walls, Transactions of the 23rd Structural Mechanics in Reactor Technology, SMiRT-23, Paper ID 712, Manchester, UK, IASMIRT, North Carolina State University, Raleigh, NC, 2016, pp. 1–10.
33. **AISC Design Guide 32**: Modular Steel-Plate Composite Walls for Safety-Related Nuclear Facilities. American Institute of Steel Construction.

Travush V.I., GORPROJECT, Moscow. Doctor of technical Sciences, Professor. Chief designer, Deputy General Director on scientific work. Vice-President of Russian Academy of Architecture and Construction Sciences, 105064, Nizhnyi Susal'nyi lane 5/5A, Moscow, Russia, e-mail: travush@mail.ru.

Травуш Владимир Ильич, ЗАО «ГОРПРОЕКТ», г. Москва, Доктор технических наук, профессор. Главный конструктор, заместитель генерального директора по научной работе. Вице-президент РААСН, 105064, Москва, Нижний Сусальный переулок, д. 5, стр. 5А, e-mail: travush@mail.ru

Arleninov P.D., Department of Reinforced Concrete and Masonry Structures, National Research Moscow State University of Civil Engineering, 129337, Yaroslavskoye shosse, 26, Moscow, Russia; JSC Research Center of Construction NIIZHB named after A.A. Gvozdev, laboratory of reinforced concrete mechanics, 109428, 6, building 5., 2nd Institutskaya str., Moscow, Russia, e-mail: arleninoff@gmail.com.

Арленинов Петр Дмитриевич, кандидат технических наук, ФГБ0У ВО «Национальный исследовательский Московский государственный строительный университет» Минобрнауки России (НИУ МГСУ), 129337, Москва, Ярославское шоссе, д. 26; заместитель заведующего лаборатории Механики железобетона, Научно-исследовательский, проектно-конструкторский и технологический институт бетона и железобетона (НИИЖБ) им. А. А. Гвоздева АО «НИЦ «Строительство», 109428, Москва, 2-я Институтская ул., д.6, корп. 5, e-mail: arleninoff@gmail.com

Desyatkin M.A, Chief Structural Engineer LLC "Inforsproekt", 115280, 19, Leninskaya Sloboda str., Moscow, Russia, e-mail: mdesyatkin@mail.ru,

Десяткин Михаил Александрович, главный конструктор ООО "Инфорспроект", 115280, Москва,ул. Ленинская Слобода, д. 19, e-mail: mdesyatkin@mail.ru

Ivashchenko A.N, Chief Structural Engineer LLC "Inforsproekt", 115280, 19, Leninskaya Sloboda str., Moscow, Russia, e-mail: a.ivaschenko@inforceproject.ru,

Андрей Николаевич Иващенко, технический директор ООО "Инфорспроект", 115280, Москва,ул. Ленинская Слобода, д. 19, e-mail: a.ivaschenko@inforceproject.ru

Kaprielov S.S., Doctor of Technical Sciences, Academician of the Russian Academy Architecture and Construction of Sciences, head of Laboratory №16 «Research Institute for Concrete and Reinforced Concrete» named after A. A. Gvozdev, JSC Research Center of Construction, 109428, 6, building 5., 2nd Institutskaya str., Moscow, Russia, e-mail: kaprielov@masterbeton-mb.ru.

Каприелов Семен Суренович, доктор технических наук, академик РААСН, заведующий лабораторией № 16 НИИЖБ им. А. А. Гвоздева АО «НИЦ «Строительство», 109428, Москва, 2-я Институтская ул., д.6, корп. 5, e-mail: kaprielov@masterbeton-mb.ru

Konin D.V., Candidate of Technical Sciences, Deputy Director for Scientific Work, Chief manager of Laboratory of High-rise Buildings and Structures of the Department of Metal Structures, Research Institute of Building Constructions (TSNIISK) Named After V. A. Koucherenko JSC Research center of Construction,109428, 6, 2nd Institutskaya str., Moscow, Russia, e-mail: konden@inbox.ru.

Денис Владимирович Конин, кандидат технических наук, заместитель Директора по научной работе, заведующий лабораторией Высотных зданий и сооружений отдела металлических конструкций, ЦНИИСК им. В.А. Кучеренко АО "НИЦ "Строительство", Москва, 2-я Институтская улица, д.6, e-mail: konden@inbox.ru

Krylov A.S., Candidate of Technical Sciences, Leading Researcher of Laboratory of High-rise Buildings and Structures, Research Institute of Building Constructions (TSNIISK) Named After V. A. Koucherenko JSC Research center of Construction, 109428, 6, 2nd Institutskaya str., Moscow, Russia, e-mail: kryl07@mail.ru.

Крылов Алексей Сергеевич, кандидат технических наук, ведущий научный сотрудник лаборатории Высотных зданий и сооружений, ЦНИИСК им. В.А. Кучеренко АО "НИЦ "Строительство", Москва, 2-я Институтская улица, д.6, e-mail: kryl07@mail.ru

Krylov S.B, Doctor of Engineering Sciences. JSC Research Center of Construction NIIZHB named after A.A. Gvozdev, Head of Laboratory of Reinforced Concrete Mechanics, 109428, 6, building 5., 2nd Institutskaya str., Moscow, Russia, e-mail: Krylov_s_b@mail.ru.

Крылов Сергей Борисович, доктор технических наук, заведующий лабораторией Механики железобетона, Научно-исследовательский, проектно-конструкторский и технологический институт бетона и железобетона (НИИЖБ) им. А. А. Гвоздева АО «НИЦ «Строительство», 109428, Москва, 2-я Институтская ул., д.6, корп. 5, e-mail: Krylov_s_b@mail.ru

Chilin I.A., Engineer, Researcher of Laboratory №16 «Research Institute for Concrete and Reinforced Concrete» named after A. A. Gvozdev, JSC Research Center of Construction, 109428, 6, building 5., 2nd Institutskaya str., Moscow, Russia, e-mail: chilin@masterbeton-mb.ru.

Sheynfeld A.V., Doctor of Technical Sciences, Advisor of the Russian Academy Architecture and Construction of Sciences. Deputy Head of Laboratory №16 «Research Institute for Concrete and Reinforced Concrete» named after A. A. Gvozdev, JSC Research Center of Construction, 109428, 6, building 5., 2nd Institutskaya str., Moscow, Russia, e-mail: sheynfeld@masterbeton-mb.ru.

Чилин Игорь Анатольевич, инженер, научный сотрудник лаборатории № 16 НИИЖБ им. А. А. Гвоздева АО «НИЦ «Строительство», 109428, Москва, 2-я Институтская ул., д.6, корп. 5, e-mail: chilin@masterbeton-mb.ru

Шейнфельд Андрей Владимирович, доктор технических наук, советник РААСН, заместитель заведующего лабораторией № 16 НИИЖБ им. А. А. Гвоздева АО «НИЦ «Строительство», 109428, Москва, 2-я Институтская ул., д.6, корп. 5, e-mail: sheynfeld@masterbeton-mb.ru.