Magazine of Civil Engineering. 2019. 87(3). Pp. 18–34
Инженерно-строительный журнал. 2019. № 3(87). С. 18–34

Magazine of Civil Engineering

ISSN 2071-0305

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.18720/MCE.87.2

# The effect of perforations on the deformability of welded beam with corrugated webs

***A.A. Bryantsev*[a*], *V.E. Absimetov*[b], *V.V. Lalin*[c],**
[a] *Kazakh Leading Academy of Engineering and Construction Inc., Almaty, Republic of Kazakhstan*
[b] *"AstanaStroyKonsalting" LLP, Astana, Kazakhstan*
[c] *Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia*
** E-mail: Bryancev8989@mail.ru*

**Keywords:** beam with corrugated web, web perforation; triangular shape of corrugations, beam deflection, finite element analysis, ring stiffener.

**Abstract.** Perforating steel beams is inevitable in some cases such as setting the technical equipment, though it decreases the carrying capacity of the element. The lack of information about the nature of the work, the values of critical stresses, the stability of the corrugated webs of the beams weakened by the perforations necessitated relevant studies for which the perforations of different diameters and with various ways of reinforcement were formed in the webs of the beams. Hence, this research focuses on the behavioral condition of welded beams with corrugated triangular webs weakened by different sized perforations at different locations. The impacts of these perforations on the transverse load-carrying capacity of the element and the suitable ways for stiffening them were investigated. An analysis is made of the influence of the edging thickness, paired vertical stiffeners at different widths of the ring stiffener on behavior of models of beams with a corrugated web with perforations. The influence of the bending of the lip around the exterior circumferential edge of the stiffener ring on the bearing capacity of beams with a corrugated web weakened by perforations was analyzed. The most effective location of the perforations along the web height has been determined.

## *1. Introduction*

The main aim of this research directed on identification behavioral condition and deformability of welded beams with corrugated triangular webs weakened by perforations.

During this research the main tasks need to defined: 1) necessity of stiffening the web and the perforation; 2) the most optimal sized of perforations, distance between perforations and types of strengthening; 3) influence of a lip around the exterior circumferential edge of the stiffener ring on bearing capacity of the beam weakened by the perforations; 4) the most effective location of the perforation along the web height.

A Corrugated beam is a beam with flanges made of different section metal and corrugated (curved) web in transverse direction [1]. Corrugated webs of beams can be with a triangular corrugation profile [2], wavy, trapezoidal [3, 4], rectangular, etc. flanges of such beams are made of rolled steel, molded sections, electric-welded pipes, reinforced concrete elements. Beams with corrugated webs are used in many countries (Table 1).

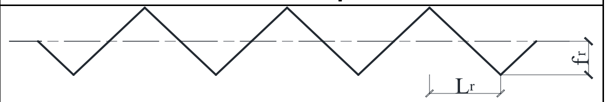
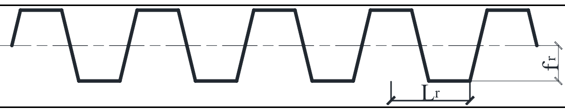
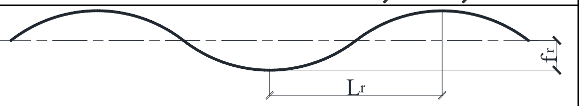
Literary sources with open access [5, 6] have a few solutions of the problems of designing perforations in the corrugated webs. There are also limited data on experimental and theoretical studies of influence of local concentrated loads and local weakening on the bearing capacity and deformation of beams. This question was mainly considered in thin-walled beams [7–13] and in beams with flat webs and with perforated webs [14, 15]. The need for perforations application in the corrugated webs is due to the fact that laying of the piping system for various purposes: water supply, heating, ventilation, air conditioning.

Bryantsev, A.A., Absimetov, V.E., Lalin, V.V. The effect of perforations on the deformability of welded beam with corrugated webs. Magazine of Civil Engineering. 2019. 87(3). Pp. 18–34. DOI: 10.18720/MCE.87.2.

Брянцев А.А., Абсиметов В.Э., Лалин В.В. Влияние отверстий на деформативность стенки сварной гофрированной балки // Инженерно-строительный журнал. 2019. № 3(87). С. 18–34. DOI: 10.18720/MCE.87.2

This open access article is licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)

***Table 1. Area of application and corrugated web shape, where $L_r$ is the length of the corrugation half-wave; $f_r$ is the height of the corrugation half-wave.***

| Beam Name | Place of Application | Web shape |
|---|---|---|
| Beams with cross-corrugated web and triangular-shaped corrugations | Kazakhstan, Russia, Tajikistan |  |
| Beams with corrugations of a trapezoidal and rectangular shape | Sweden, the USA, Japan, Finland |  |
| Beams with cross-corrugated web and wavy-shaped corrugations | Austria, Ukraine, Poland, Russia |  |

The issues of the perforations affect the work of the beam web which are performed according to the Vierendeel principle or the four-angular bend [16], are studied in various works [17–19]. Also, the problems of placing and stiffening of perforations in the corrugated webs of trapezoidal and wavy shape of corrugations were solved in different countries by many scientists [20, 21]. However, except the study [16], for beams with a corrugated web and corrugations of a triangular shape no more study was revealed.

In view of the absence in the regulatory documents on the territory of the Republic of Kazakhstan and Russia a proper explanation of the pitch, diameter and methods of reinforcing perforations, there is a need to conduct a study of the influence of the diameter and pitch of perforations on the deformability of the corrugated beam, in order to develop a methodology for designing welded corrugated beams, weakened by perforations.

The stressed state of the corrugated web in the perforation zone is a separate issue requiring additional studies that take into account the ratio of the diameter of the perforations and the beam web height, the perforations pitch, the stiffness of the element supporting the shape of the perforation.

## *2. Methods*

Experimental studies of corrugated beams are a very important part of the substantiation of various hypotheses about the principles of work and the effectiveness of the design decisions [22–26]. There are no specific requirements on the number, pitch and diameter of the perforations in both Kazakhstan and foreign building regulations.

The experimental study was performed on two support beams with a corrugated web with a triangular shape of the corrugations, without perforations and weakened by three perforations. Three circular perforations with a diameter of 0.5$h_w$, where $h_w$ is the web height (Figure 1), were provided to ensure the various types of communication passage in the beams webs. Since there is no exact method for calculating the corrugated beams with weakening, then the beams with thin corrugated webs weakened by perforations require appropriate field tests for the practical application in construction. The geometric parameters, materials, loads and boundary conditions adopted during the experiment are presented below.

As a result of theoretical and experimental studies carried out at the beginning of the 90s by the Institute “Proektstalkonstrukciya” [27] based in its own laboratories, the use of corrugated webs in girder structures has expanded significantly. The test was performed on large-scale models (scale 1:3) of corrugated beams of constant section (flange is 220×10 mm, web is 840×1.9 mm) with a span of 8400 mm. The first beam B-1 was accepted without perforations. Three circular perforations with a diameter of 0.5$h_w$, which edges were reinforced with stiffeners made of strip steel with a cross section of 85×3 mm, are formed in the web of the second beam B-2. The maximum allowable deflection of the beam is assumed to be 1/220$L$, and is equal to 38.2 mm.

In the perforation zone in four sections of the web, rectangular sockets of three electrical strain gauges with a base of 10 mm were glued along the length. The indications of electrical strain gauges were taken visually by a CTM-5 device, and were also output to Iskra-108D printer and to a punched tape for further processing by a computer. The load at the time of testing in the elastic stage of the beam behavior was measured using a DOSM-5 model dynamometer with an accuracy class of 1.5 and duplicated using M100 manometers. Displacements of beams in the plane of the load action were measured using PAO-6 deflectometer with a division value of 0.01 mm. The deflectometers measured the vertical displacement and were located in sections where the load was applied, as well as on supports. The general view of the beams and their geometric dimensions is given in Figure 1.

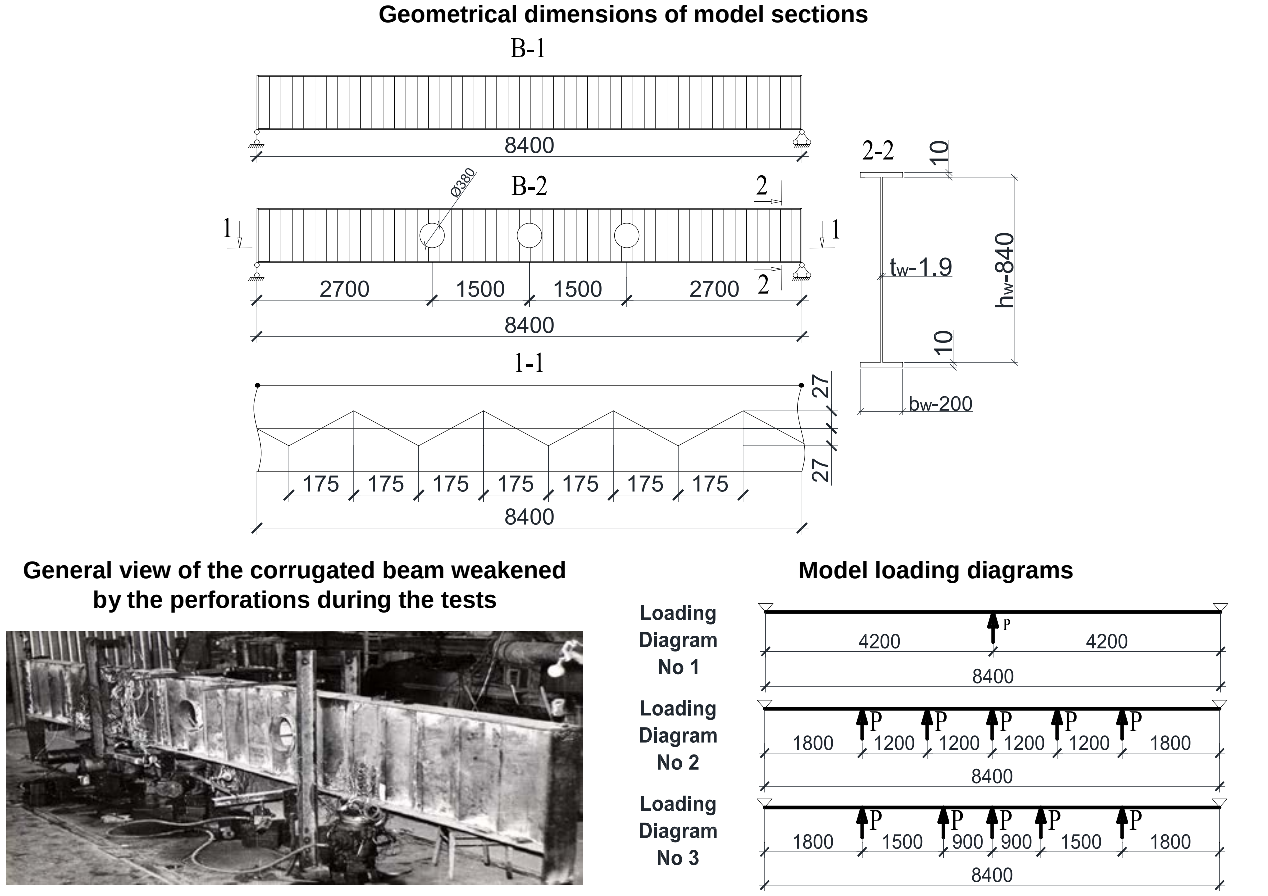



**Figure 1. Data on the geometric dimensions of the model section, the general view of the beam during the tests and the tested models loading diagrams.**

The web corrugations of triangular shape with roundings in the peaks had a wave length $L_r$ = 50 mm and a wave height $f_r$ = 54 mm. Material of the web and flanges was taken steel S245 in accordance with Russian State Standard GOST 27772 [28] with the following characteristics: yield strength $\sigma_y$ = 245 N/mm$^2$ and ultimate strength $\sigma_u$ = 370 N/mm$^2$. The Beams were made in the laboratory for metal structures testing. The general view of the corrugated beam weakened by the perforations, is given in Figure 2.

The beams were loaded with DGO 100/2/G50H A0CM5 hydraulic jacks through steel plates of 100×20 mm long equal to the width of the beam flange ($L$ = 200 mm). To ensure equal loads jacks installed symmetrically relative to the middle of the beam, were connected by hoses and loaded manually with a single pump. Loading diagrams are shown in Figure 1.

The beams deformation property was also studied along with the study of the beam elements stressed state, since there is little information about the beams deformation property with thin corrugated webs, and especially weakened by perforations; and their interest in construction practice is special. The effect of local wall stability loss on the structure behavior was not taken into account in this work.

The performed tests make it possible to conduct a comparative analysis of the beams deformation property (Figure 2) of the same cross-section with perforations in the web and without such perforations under the same operating conditions, as well as to check the computer simulation data of the tests in the LIRA-SAPR 2017 software package with the aim of further usage of this program as the main one for further numerical investigations of the corrugated beam weakened by circular perforations of different pitch and diameter.

***a)*** ***b)***

**Figure 2. The model of beams: a) B-1; b) B-2.**

Table 2 presents the values of the bending moments in the middle of the span $M_e$, the transverse force at the supports $Q_e$, the stresses in the flanges $\sigma_{\max}$, the stresses in the web $\tau_{\max}$, as well as the experimental $Y_e$, theoretical $Y_t$ and computer $Y_c$ deflections of the B-1 beam without the perforations ones. The values of deflections in the middle of the B-2 beam with perforations for 1, 2 and 3 loading diagrams of experimental $Y_e^*$ and computer $Y_c^*$ data in the linear region of behavior are also presented. For the numerical experiment, the following grid was adopted: 0.04×0.09 m, in the area of the perforations, the grid is reduced to 2 times. Computer simulation of the beams was performed using the program LIRA-SAPR, program for the finite element analysis. The boundary conditions were applied to both ends of the beam model at the nodes of the end plate surface by limiting the required degrees of freedom. The beam at both ends has a fastening along the axes $Y$ and $Z$. The material of the web and flanges is S245 steel in accordance with Russian State Standard GOST 27772 [28]. The yield strength is $\sigma_y$ = 245 N/mm$^2$ the elastic modulus is $E$ = 206000 MPa and the Poisson ratio is 0.3. The values of the experimental stresses $\sigma_{\max}$ and $\tau_{\max}$ resented in Table 2 were obtained in the study of beams with a corrugated web weakened by perforation.

***Table 2. The results of the experimental data.***

| Loading diagram No. | Total load on the beam $\Sigma Q$, kN | The bending moment in the middle of the span $M_e$, kNm | The transverse force at the supports $Q_e$, kN | The stress in the flanges $\sigma_{\max}$, MPa | The stress in the web $\tau_{\max}$, MPa | Deflection (mm) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $Y_t$ B-1 | $Y_e$ B-1 | $Y_c$ B-1 | $Y_e^*$ B-2 | $Y_c^*$ B-2 | $Y_e^* / Y_c^*$ |
| 1 | 40 | 84 | 20 | 49.4 | 12.5 | 3.41 | 4 | 4.28 | 3.44 | 5.15 | – |
| 2 | 150 | 207 | 75 | 121.8 | 47.0 | 12.8 | 9.5 | 12 | 12.7 | 13.6 | 0,93 |
| 2 | 200 | 276 | 100 | 162.4 | 62.7 | 17.1 | 13.2 | 16 | 17.1 | 18.1 | 0,94 |
| 3 | 250 | 360 | 125 | 211.8 | 78.3 | 21.4 | 18.6 | 20.5 | 25.1 | 23.8 | 1,05 |

Analysis of the data in Table 2 shows that the deformation property of the tested B-2 beam in the linear region of behavior $Q_e \approx$ 0.65–0.7 $Q_{e,\max}$ is 20–30 % larger than that of the similar B-1 beam without weakening, where $Q_{e,\max}$ is maximum experimental load. The value of the relative deflection is 1/430$L$. With further loading, the B-2 beams deformation property was 3–50 % higher than the deformation property of the B-1 beam without the perforation. The first group of limit state came when the deflections were equal to 1/225$L$.

Comparative analysis of experimental $Y_e^*$ and computer $Y_c^*$ data on deflections for the tested B-2 beam with perforations in loading diagram No. 2 and No. 3 gives a difference in deflections on average no more than 6 %. The data obtained allow using this program as the main one for further numerical studies of corrugated beam with different diameter, type and pitch of perforations in the corrugated web.

According to the above analysis, it can be concluded that stiffening of the web in the areas between the flanges and stiffening element of the perforation by the pair stiffeners is necessary in order to avoid local buckling under the concentrated load in the perforation zone.

## *2.1. Parametric study of the corrugated beam with different diameter, type and pitch of perforations in the corrugated web*

The study of the stress-strain state, the bending moment, the linear analysis of beams with a corrugated metal webs was carried out by various scientists [2–32].

Numerical parametric study of the beam web with corrugation of triangular shape includes analysis of basically 28 models. Of these 28 models, 1 beam the model without web perforations and 27 models with perforations of different sizes and they are located at different distances from each other.

According to above analysis, it is necessary to check the effect of the diameter of 0.25$h_w$, 0.5$h_w$ and 0.75$h_w$ from the web height and the pitch of the perforations with two diameters ($2d$), three diameters ($3d$) and four diameters ($4d$) taken as the distance between the centers of the perforations on the corrugated web with the corrugations of triangular shape operation. The center of the perforations is located in the middle of the web height.

Numerical simulation of the beams was performed using the program LIRA-SAPR, program for the finite element analysis, which includes the requirements for constructions in accordance with EN-1993-1-5:2006 [33]. This program can be used to solve various tasks, from simple linear analysis and on out to complex nonlinear analysis requiring consideration of various manufacturing deviations and material errors. The parametric study was performed for the beam taking into account the various sizes of the perforations in the beam web, distances between the perforations, existence and absents of the perforation stiffening, as well as for the corrugated beam without web perforation. The ability of the beam web with and without the perforation to withstand the load was considered and an assessment of the effect of web flexibility in accordance with [33] was performed.

For numerical simulation was accepted the beam with a web height $h_w$ = 840 mm and a web thickness $t_w$ = 1.9 mm. The web corrugations of triangular shape with roundings in the peaks had a wave length $L_r$ = 350 mm and a wave height $f_r$ = 54 mm (Figure 3). The material of the web and flanges is S245 steel in accordance with Russian State Standard GOST 27772 [28]. The yield strength is $\sigma_y$ = 245 N/mm$^2$ and the ultimate strength is$\sigma_u$ = 370 N/mm$^2$.

Finite element models adopted for beams with the corrugations of triangular shape with and without perforations are given in Figure 3.

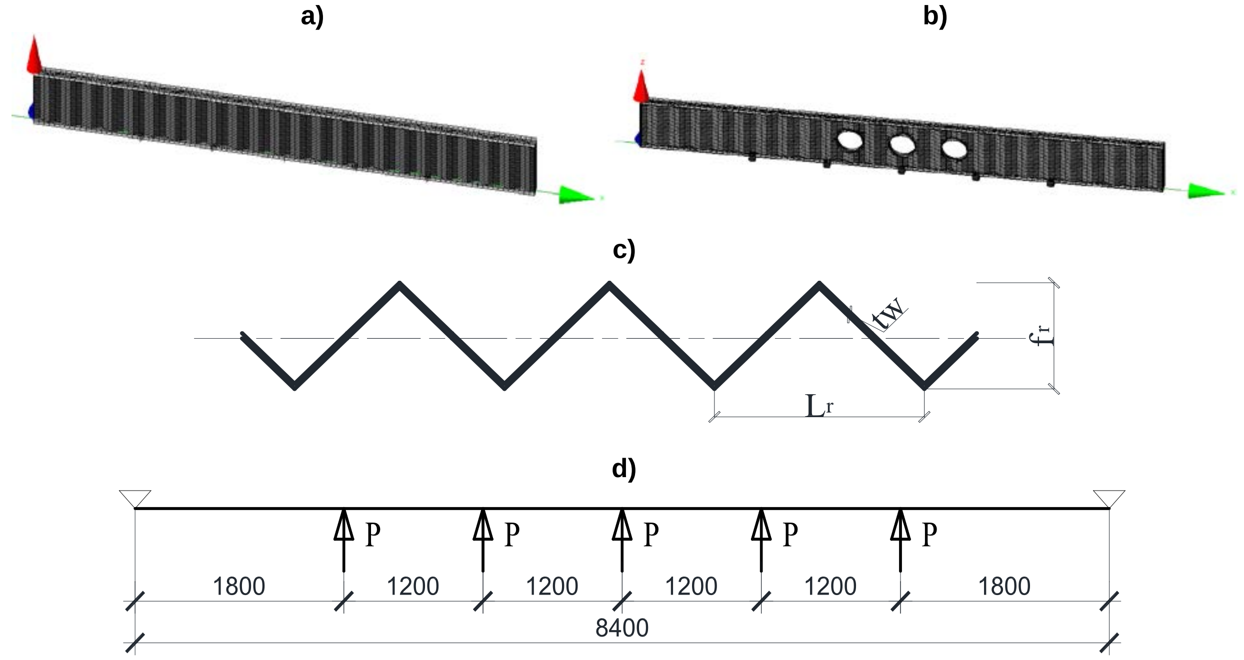



**Figure 3. Models adopted for the beams analysis, where a) M-1 corrugated beam with a triangular profile without perforations; b) from M-2 to M-28 corrugated beams with a triangular profile weakened by perforations; c) values of length, height and thickness of web with corrugations of triangular shape adopted in computer simulation; d) model loading diagram for parametric study.**

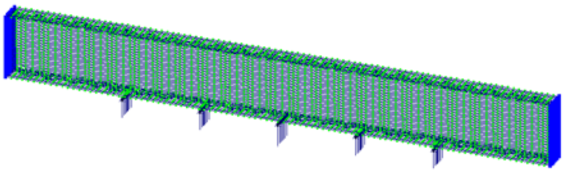
The corrugated beam of constant section (flanges are 200×10 mm, webs are 840×1.9 mm) are made with span of 8400 mm. Two end plates with a thickness $t$ = 20 mm is accepted at the ends of each model. Stiffening ring thickness is 3 mm. Paired vertical stiffeners width and thickness is 85×3 mm. Other characteristics of the investigated beams are shown in Table 3.

The load is applied through steel plates of 100×20 mm long equal to the width of the beam flange ($L$ = 200 mm), which is in direct contact with the surface of the flange. The load is transmitted at five points from the bottom to the top. The load is applied in the beam center, as well as at a distance from the center in both directions of 1200 mm in accordance with the model loading diagram (Figure 3, 4). The boundary conditions were applied to both ends of the beam model at the nodes of the end plate surface by limiting the required degrees of freedom. The beam at both ends has a fastening along the axes $Y$ and $Z$.

The tested beam has three circular perforations; the perforations' centers are located in the middle of the web height. The distance between the centers of the perforations is assumed to be $2d$, $3d$ and $4d$ of the perforations. One of the perforations has a constant location in the center of the beam at a distance of 4200 mm from the left and right support to the perforation center. The material of the web and flanges is S245 steel in accordance with GOST 27772 [28]. The yield strength is $\sigma_y$ = 245 N/mm$^2$, the elastic modulus is $E$ = 206000 MPa and the Poisson ratio is 0.3. For the beam models with the length of 8400 mm, the maximum allowable deflection is 1/220$L$ or 38.2 mm. Loading ($Q$) of models is from 50 kN to 350 kN. Loading step is 50 kN. The maximum load value was accepted on the basis of the maximum load that the beam withstood during the experiment. The ultimate strength of the models presented above was studied using finite element analysis.

***Table 3. Characteristics of the investigated beams.***

| Grade of the model | Diameter of the perforation | Stiffening | Perforation pitch | Stiffening ring width (mm) |
|---|---|---|---|---|
| M-1 | without web perforations | – | – | – |
| M-2 | $0.25h_w$ | without the perforations stiffening | $2d$ | 50 |
| M-3 | $0.5h_w$ | without the perforations stiffening | $2d$ | 50 |
| M-4 | $0.75h_w$ | without the perforations stiffening | $2d$ | 50 |
| M-5 | $0.25h_w$ | perforation with edging | $2d$ | 50 |
| M-6 | $0.5h_w$ | perforation with edging | $2d$ | 50 |
| M-7 | $0.75h_w$ | perforation with edging | $2d$ | 50 |
| M-8 | $0.25h_w$ | perforation with edging and paired vertical stiffeners | $2d$ | 50 |
| M-9 | $0.5h_w$ | perforation with edging and paired vertical stiffeners | $2d$ | 50 |
| M-10 | $0.75h_w$ | perforation with edging and paired vertical stiffeners | $2d$ | 50 |
| M-11 | $0.25h_w$ | without the perforations stiffening | $3d$ | 110 |
| M-12 | $0.5h_w$ | without the perforations stiffening | $3d$ | 110 |
| M-13 | $0.75h_w$ | without the perforations stiffening | $3d$ | 110 |
| M-14 | $0.25h_w$ | perforation with edging | $3d$ | 110 |
| M-15 | $0.5h_w$ | perforation with edging | $3d$ | 110 |
| M-16 | $0.75h_w$ | perforation with edging | $3d$ | 110 |
| M-17 | $0.25h_w$ | perforation with edging and paired vertical stiffeners | $3d$ | 110 |
| M-18 | $0.5h_w$ | perforation with edging and paired vertical stiffeners | $3d$ | 110 |
| M-19 | $0.75h_w$ | perforation with edging and paired vertical stiffeners | $3d$ | 110 |
| M-20 | $0.25h_w$ | without the perforations stiffening | $4d$ | 180 |
| M-21 | $0.5h_w$ | without the perforations stiffening | $4d$ | 180 |
| M-22 | $0.75h_w$ | without the perforations stiffening | $4d$ | 180 |
| M-23 | $0.25h_w$ | perforation with edging | $4d$ | 180 |
| M-24 | $0.5h_w$ | perforation with edging | $4d$ | 180 |
| M-25 | $0.75h_w$ | perforation with edging | $4d$ | 180 |
| M-26 | $0.25h_w$ | perforation with edging and paired vertical stiffeners | $4d$ | 180 |
| M-27 | $0.5h_w$ | perforation with edging and paired vertical stiffeners | $4d$ | 180 |
| M-28 | $0.75h_w$ | perforation with edging and paired vertical stiffeners | $4d$ | 180 |



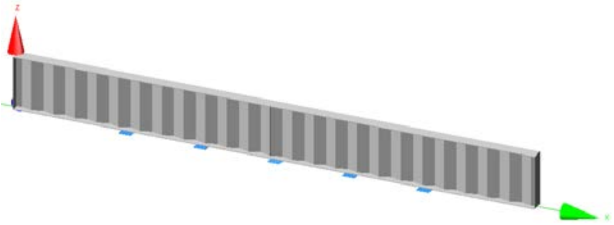


**Figure 4. Diagram of model loading.**

## *3. Results and Discussion*

Maximum allowable deflection is not reached when analyzing the obtained data for the M-1 beam model. The deflection for the M-1 beam model under the maximum load effect is 28 mm.

Figures 5–7 show the load-deflection dependence of the middle from M-2 to M-28 beam models with $2d$, $3d$ and $4d$ perforation pitch when operating in the elastic stage. Table 4 shows the shape of deflection of some models.

The Figure 5 shows the load-deflection dependence of the middle from M-2 to M-10 beam models with $2d$ perforation pitch.

The Figure 6 shows the load-deflection dependence of the middle from M-11 to M-19 beam models with $3d$ perforation pitch.

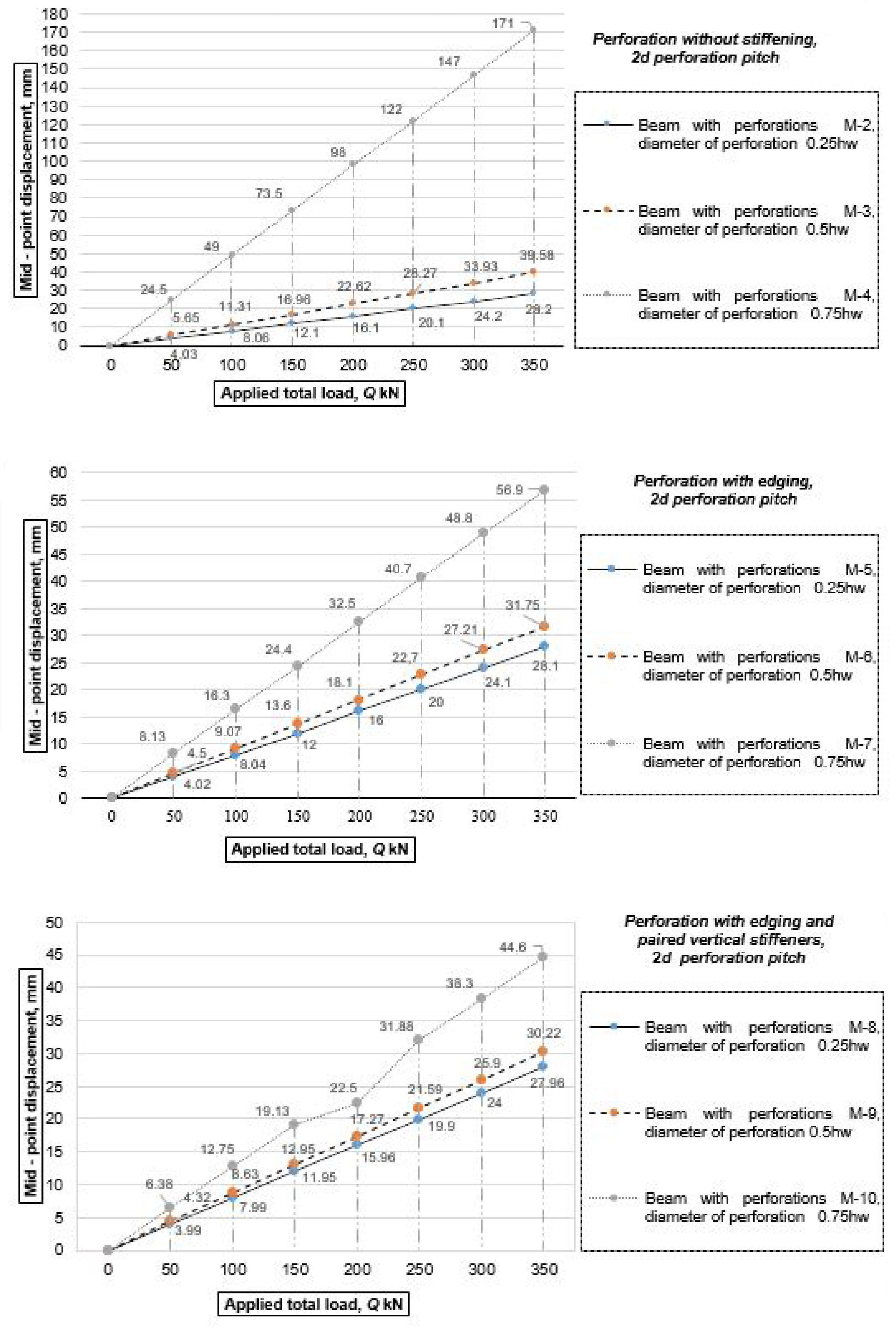



**Figure 5. Displacement and applied total load value dependence from M-2 to M-10 beam models with the 2$d$ perforation pitch without the perforations stiffening, perforation with edging and perforation with edging and paired vertical stiffeners.**

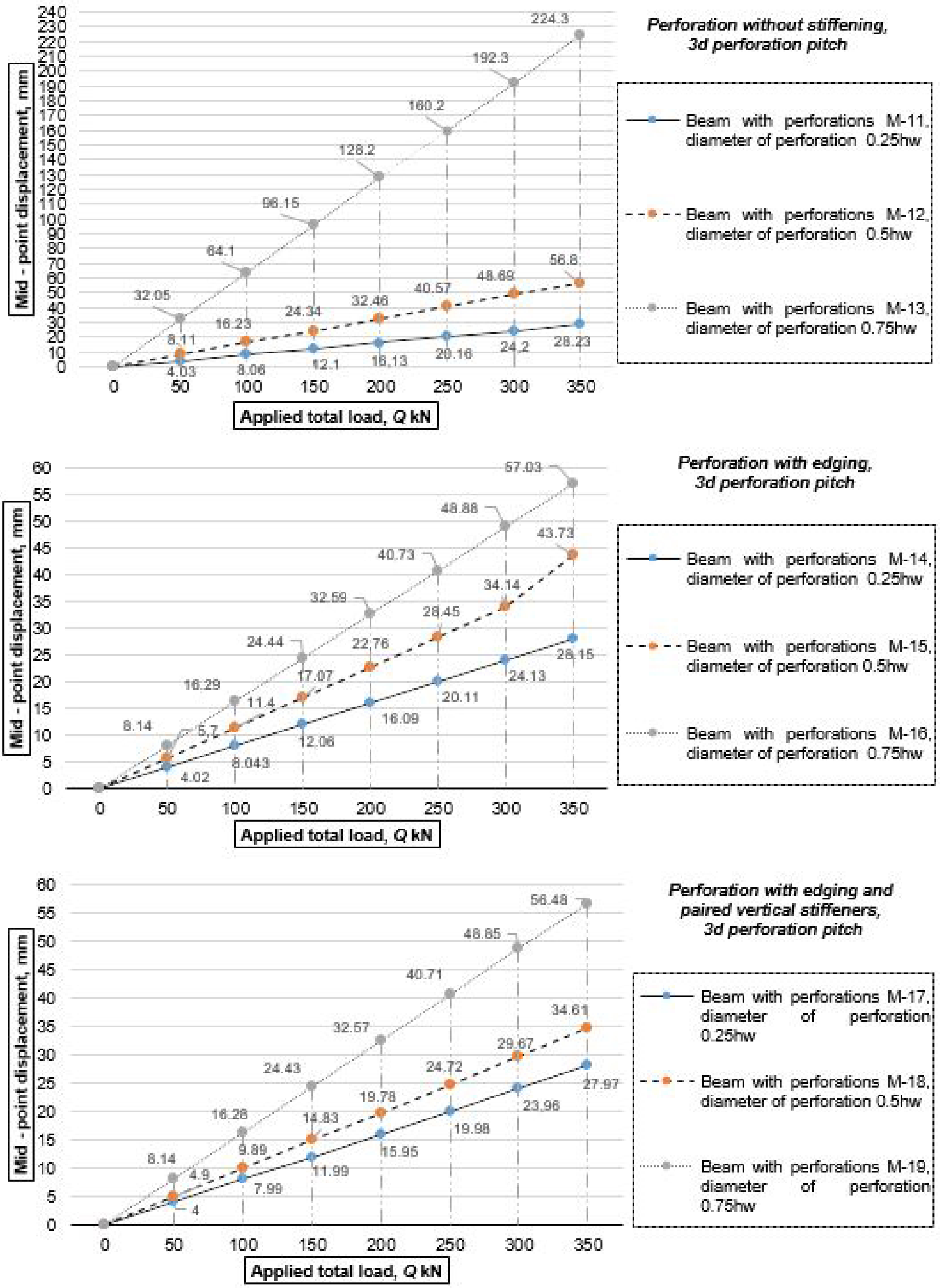



**Figure 6. Displacement and applied total load value dependence from M-11 to M-19 beam models with the 3$d$ perforation pitch without the perforations stiffening, perforation with edging and perforation with edging and paired vertical stiffeners.**

The Figure 7 shows the load-deflection dependence of the middle from M-20 to M-28 beam models with $4d$ perforation pitch.

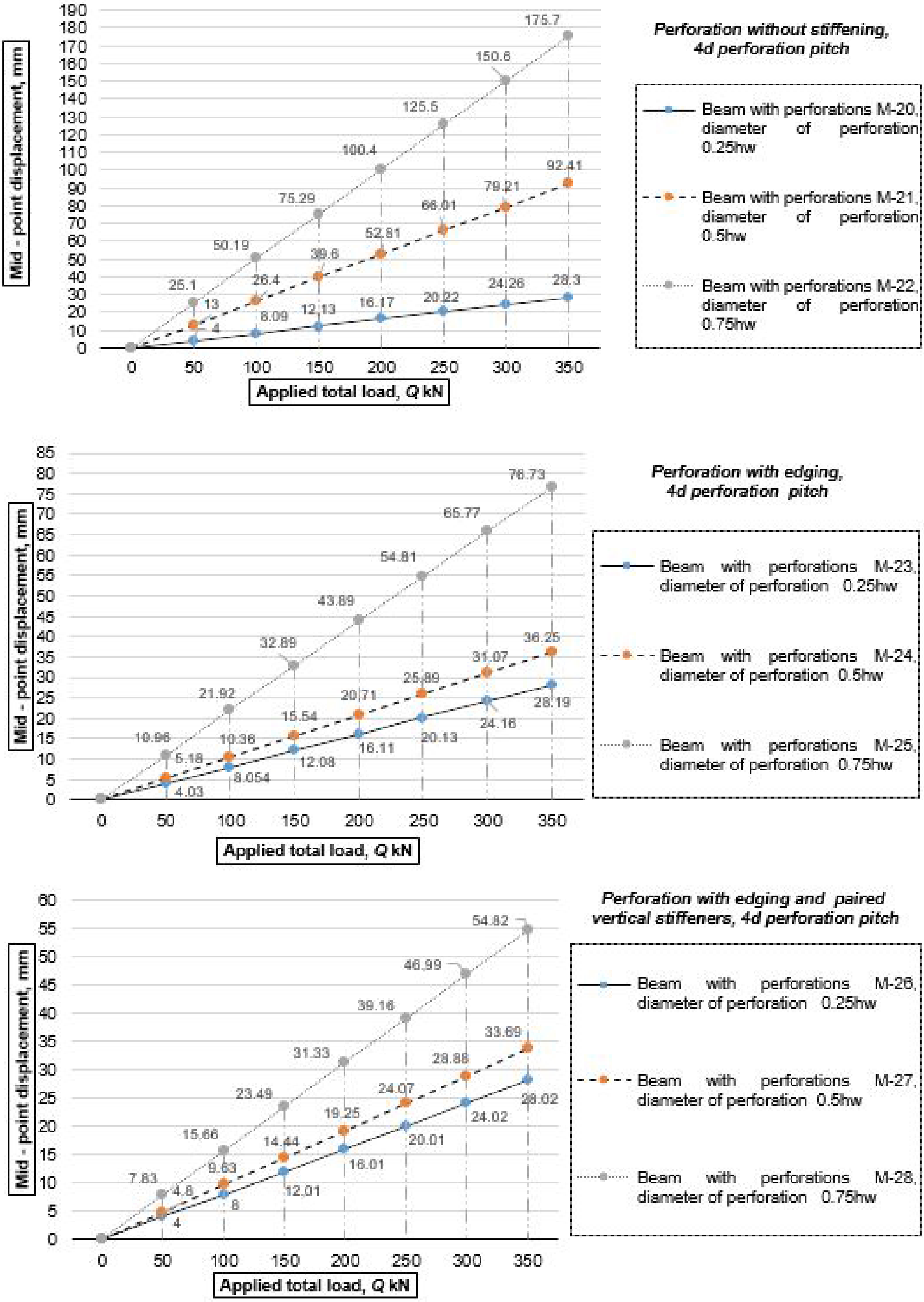
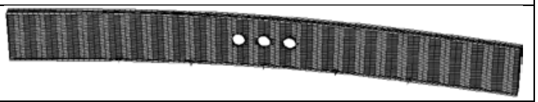
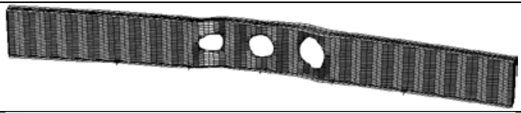
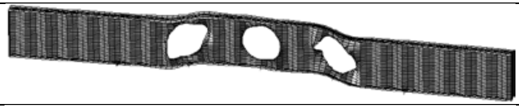
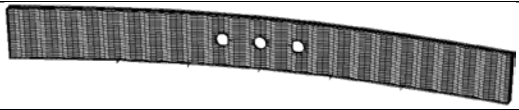
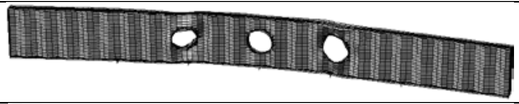
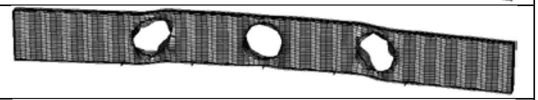
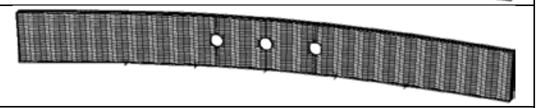
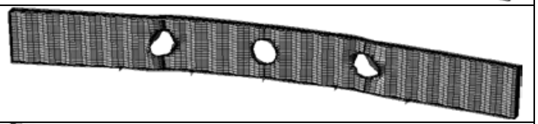
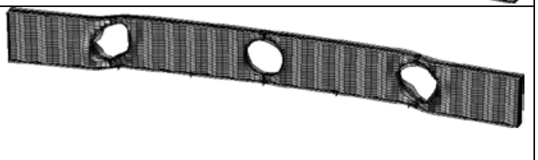



**Figure 7. Displacement and applied total load value dependence from M-20 to M-28 beam models with the 4$d$ perforation pitch without the perforations stiffening, perforation with edging and perforation with edging and paired vertical stiffeners**

***Table 4. Deflection shape of beam models with different diameters and methods of stiffening.***

| Grade of the Model | Diameter of the perforation | Perforation pitch | Stiffening | Deformation shape |
|---|---|---|---|---|
| M-2 | $0.25h_w$ | $2d$ | without the perforations stiffening |  |
| M-3 | $0.5h_w$ | $2d$ | without the perforations stiffening |  |
| M-4 | $0.75h_w$ | $2d$ | without the perforations stiffening |  |
| M-14 | $0.25h_w$ | $3d$ | perforation with edging |  |
| M-15 | $0.5h_w$ | $3d$ | perforation with edging |  |
| M-16 | $0.75h_w$ | $3d$ | perforation with edging |  |
| M-26 | $0.25h_w$ | $4d$ | perforation with edging and paired vertical stiffeners |  |
| M-27 | $0.5h_w$ | $4d$ | perforation with edging and paired vertical stiffeners |  |
| M-28 | $0.75h_w$ | $4d$ | perforation with edging and paired vertical stiffeners |  |

It was decided to begin the analysis of beam models with corrugated web with $2d$ perforations pitch without perforations stiffening to determine the most effective version of the model of corrugated beam with perforations. The obtained data allow to make conclusions that the best result was shown by the M-2 model with a diameter of the perforations of $0.25h_w$ with maximum displacement does not exceeding the maximum permissible one. The deflection of the M-3 beam model with the perforation pitch of $2d$ is greater by 28.8 % than that of the M-2 beam model, and the deflection of the M-4 beam model with the perforation pitch of $0.75h_w$ is greater than that of the M-2 beam model by 510.7 %.

In the same way, the work of other models of beams ranging from M-4 to M-28 was investigated. The results were carefully analyzed; the conclusions are given below.

According to the analysis of beam models with perforations of various diameters and pitches, the following main conclusions can be drawn:

– the most effective model of a beam with the diameter of the perforation of $0.25h_w$ with $2d$ pitch was the M-8 beam model with the actual shearing stress in the section of the corrugated web with the perforation $\tau_{act} \leq 0.1R_s$ under the maximum load effect $Q$ = 350 kN, and the maximum possible load $Q_{\max}$ on this beam model for achieving the limit deflection is equal to $Q_{\max}$ = 478.2 kN; with $3d$ pitch was the M-17 beam model with $\tau_{act} \leq 0.14R_s$, and the maximum possible load $Q_{\max}$ = 478 kN; with $4d$ pitch was the M-26 beam model with $\tau_{act} \leq 0.19R_s$, and the maximum possible load $Q_{\max}$ on this beam model for achieving the limit deflection is equal $Q_{\max}$ = 477.2 kN. All beam models with the perforations stiffened by edging with sheet steel and paired stiffeners located on both sides of the perforation, showed the best results. In the design among these three models of beams, M-8 beam model can be recommend having the best performance with the diameter of the perforation of $0.25h_w$, is minimal, it is recommended to perform them with edging;

– the most effective model of a beam with the diameter of the perforation of $0.5h_w$, with $2d$ pitch was the M-9 beam model with $\tau_{act} \leq 0.29R_s$, and the maximum possible load $Q_{\max}$ on this beam model for achieving the limit deflection is equal to $Q_{\max}$ = 442.4 kN; with $3d$ pitch was the M-18 beam model with $\tau_{act} \leq 0.43R_s$, and the maximum possible load $Q_{\max}$ on this beam model for achieving the limit deflection is equal to $Q_{\max}$ = 386.3 kN; with $4d$ pitch was the M-27 beam model with $\tau_{act} \leq 0.58R_s$, and the maximum possible load $Q_{\max}$ on this beam model for achieving the limit deflection is equal to $Q_{\max}$ = 396.8 kN. All specified models with the perforations stiffened by edging with sheet steel and paired stiffeners located on both sides of the perforation, showed the best results. In the design among these three models of beams, M-9 beam model can be recommend, having the best performance with the diameter of the perforation of $0.5h_w$, and $2d$ pitch;

– the most effective model of a beam with the diameter of the perforation of $0.75h_w$, with $2d$ pitch was the M-10 beam model with $\tau_{act} \leq 0.58R_s$, but the maximum possible load $Q_{\max}$ on this beam model for achieving the limit deflection is equal to $Q_{\max}$ = 299.6 kN; with $3d$ pitch was the M-19 beam model with $\tau_{act} \leq R_s$, under the load of $Q_{\max}$ = 270 kN; with $4d$ pitch was the M-28 model $\tau_{act} \leq R_s$, under the load of $Q_{\max}$ = 202 kN. The M-19 and M-29 models with the perforations stiffened by edging with sheet steel and paired stiffeners located on both sides of the perforation showed that the yield point of steel along the shearing stress was reached. When designing, for the listed beam models stiffened by this method, it is not recommended to apply them without additional measures to increase the bearing capacity.

In general, all models showed reduction in resistance of the elements to buckling with increase of the perforation size. Therefore, to decrease the deflections and increase the stability and strength of the beam weakened by the perforations it is necessary to stiffen the perforation. Analysis of behavior of the beam models with perforations under a concentrated load showed reduction of the beam bearing capacity with an increase of the perforations pitch from $2d$ to $4d$ and the diameter of the perforations from $0.25h_w$ to $0.75h_w$. The most optimal diameter of the perforation when designing can be the diameter of the perforation of $0.25h_w$ and $0.5h_w$ with $2d$ or $3d$ perforations pitch. Stiffening the perforation by edging with sheet steel, as well as the perforation stiffening with paired vertical stiffeners is necessary to increase the load-bearing capacity of the corrugated beam weakened by perforations. In the case of an acute need of the perforation with a diameter of $0.75h_w$ it is recommended to use steel with higher strength characteristics in order to increase the bearing capacity and reduce the laboriousness of its manufacture.

In scientific works [17–22], there are no requirements for theoretical and experimental studies on the effect of stiffened perforations on the bearing capacity of the beam with cross-corrugated web with the corrugations of a triangular shape. Therefore, the issue of stiffening of the perforations requires special attention and further studies.

Table 5 shows the result of the obtained deflection data of beam models with corrugated web for perforations with the diameter of $0.25h_w$, $0.5h_w$ and $0.75h_w$ for $2d$ perforations pitch when the perforation is stiffened with ring stiffener and parallel stiffeners with a lip around the exterior circumferential edge of the stiffener ring and without a lip around the exterior circumferential edge of the stiffener ring with different width of the stiffening ring.

The most effective thickness of the edging and stiffeners for the perforation with the diameter of $0.25h_w$, for $2d$ perforations pitch is the thickness of 2 to 4 mm; for the perforation with the diameter of $0.5h_w$, for $2d$ perforations pitch is from 4 to 6 mm; for the perforation with the diameter of $0.25h_w$, for $2d$ perforations pitch is the thickness from 6 to 8 mm.

Figure 8 shows the form for stiffening of beams with corrugated web weakened by circular perforations. Figure 8 (a) shows edging by stiffening ring without a lip around the exterior circumferential edge of the ring and Figure 8 (b) shows edging by stiffening ring with a lip around the exterior circumferential edge of the ring. The ring stiffener provides resistance to web buckling inward.

Figure 9 shows the results of behavior analysis of the M-1 beam models with corrugated web without perforation, the M-3 beam model with the diameter of the perforation of $0.5h_w$ without perforation stiffening, M-6, M-9 beam models with various perforation stiffening options, as well as beam model with elements of the lip around the exterior circumferential edge of the ring stiffener. There is reduction in deflection in all models of beams with perforations stiffened with ring stiffeners of different thickness and width, stiffeners in comparison with models without stiffening. In addition, the deflection reduction was obtained by using a ring stiffener with elements from the lip around the exterior circumferential edge of the ring.

***Table 5. Deflections of beams with and without lips.***

| Grade of the model | Perforation diameter and pitch | Total load, (kN) | Stiffening ring width (mm) | Thickness of stiffening ring and stiffeners without a lip around the exterior circumferential edge of the ring (mm) | Deflection without lip (mm) | Thickness of a lip around the exterior circumferential edge of the ring (mm) | Deflection with lip (mm) |
|---|---|---|---|---|---|---|---|
| M-8 | $0.25h_w$, $2d$ | 350 | 50 | 2 | 28.07 | 2 | 28.03 |
| | | | | 4 | 28.01 | 4 | 27.96 |
| | | | | 6 | 27.97 | 6 | 27.91 |
| | | | | 8 | 27.94 | 8 | 27.88 |
| | | | | 10 | 27.91 | 10 | 27.86 |
| | | | 75 | 2 | 28.06 | 2 | 28.04 |
| | | | | 4 | 28 | 4 | 27.96 |
| | | | | 6 | 27.96 | 6 | 27.91 |
| | | | | 8 | 27.92 | 8 | 27.88 |
| | | | | 10 | 27.89 | 10 | 27.86 |
| | | | 100 | 2 | 28.06 | 2 | 28.04 |
| | | | | 4 | 27.99 | 4 | 27.99 |
| | | | | 6 | 27.94 | 6 | 27.93 |
| | | | | 8 | 27.92 | 8 | 27.89 |
| | | | | 10 | 27.92 | 10 | 27.86 |
| M-9 | $0.5h_w$, $2d$ | 350 | 110 | 2 | 31.32 | 2 | 29.17 |
| | | | | 4 | 29.93 | 4 | 28.67 |
| | | | | 6 | 29.28 | 6 | 28.43 |
| | | | | 8 | 28.89 | 8 | 28.27 |
| | | | | 10 | 28.64 | 10 | 28.15 |
| | | | 165 | 2 | 31.28 | 2 | 28.8 |
| | | | | 4 | 29.62 | 4 | 28.42 |
| | | | | 6 | 29.05 | 6 | 28.24 |
| | | | | 8 | 28.73 | 8 | 28.11 |
| | | | | 10 | 28.51 | 10 | 28.02 |
| | | | 220 | 2 | 31.16 | 2 | 28.72 |
| | | | | 4 | 29.39 | 4 | 28.38 |
| | | | | 6 | 28.89 | 6 | 28.21 |
| | | | | 8 | 28.62 | 8 | 28.09 |
| | | | | 10 | 28.43 | 10 | 28 |
| M-10 | $0.75h_w$, $2d$ | 350 | 180 | 2 | 67.55 | 2 | 35.94 |
| | | | | 4 | 44.32 | 4 | 32.2 |
| | | | | 6 | 35.85 | 6 | 30.89 |
| | | | | 8 | 32.85 | 8 | 30.16 |
| | | | | 10 | 31.32 | 10 | 29.68 |
| | | | 270 | 2 | 69.68 | 2 | 33.47 |
| | | | | 4 | 43.62 | 4 | 31 |
| | | | | 6 | 34.7 | 6 | 30.04 |
| | | | | 8 | 32.03 | 8 | 29.49 |
| | | | | 10 | 30.72 | 10 | 29.12 |
| | | | 360 | 2 | 70.83 | 2 | 33.29 |
| | | | | 4 | 42.94 | 4 | 30.94 |
| | | | | 6 | 33.84 | 6 | 30.01 |
| | | | | 8 | 31.44 | 8 | 29.47 |
| | | | | 10 | 30.27 | 10 | 29.10 |

To determine the perforation location effect on the stiffness of the corrugated web with corrugations of triangular shape, it was decided to displacement the center of the perforation by 100 mm towards the tension flange and by 100 mm towards the compressed flange. The diameter of $0.5h_w$ has been adopted as the diameter of the models perforation since the perforation with a diameter of $0.25h_w$ does not have a significant effect on the corrugated web behavior. The $2d$, $3d$ and $4d$ is adopted as considered perforation pitch. The perforation is edged with stiffening ring of 165 mm width, 3 mm thick with the lip around the exterior circumferential edge of the ring, as well as with stiffeners of 10 mm thick. The web thickness was accepted 1.9 mm. The data obtained for the deflection of the models are summarized in Table 6.

a) b)

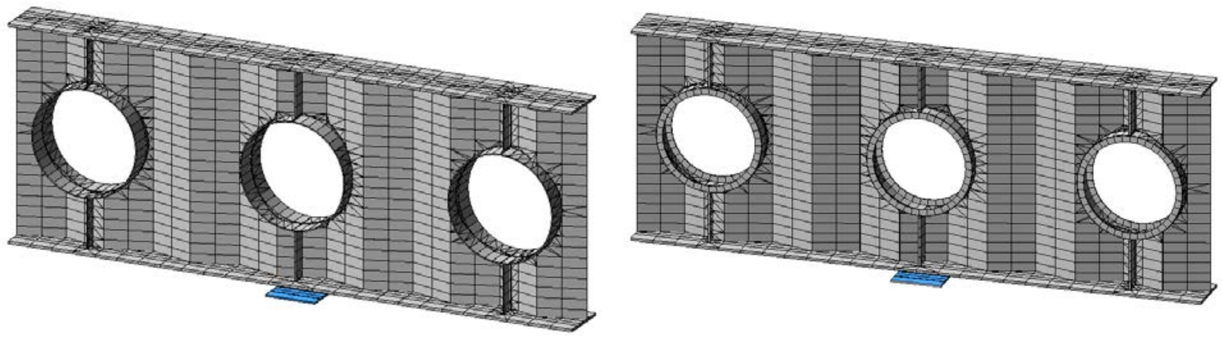


**Figure 8. The form for stiffening of circular perforation with the diameter of 0.5$h_w$ a) edging by stiffening ring and stiffening without a lip around the exterior circumferential edge of the ring b) edging by stiffening ring and stiffening with a lip around the exterior circumferential edge of the ring**

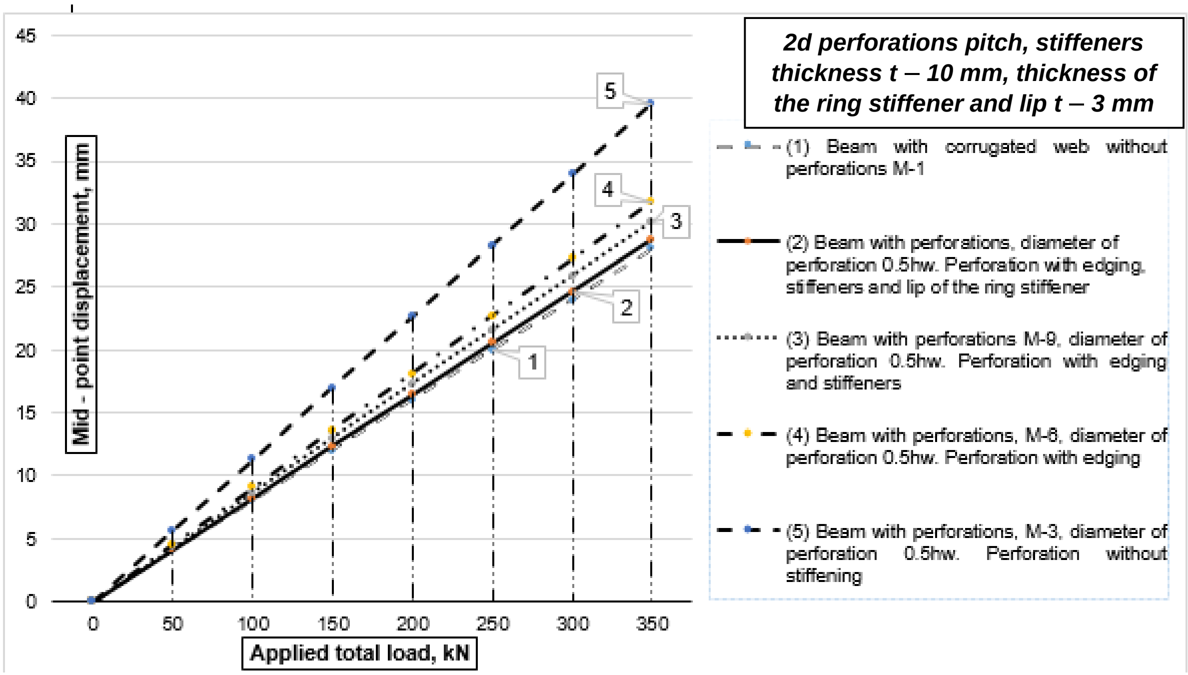



**Figure 9. Effectiveness of the perforation stiffening effect on behavior of the beam with corrugated web.**

***Table 6. The perforation location effect along the height of the corrugated web on the deflection of the beam with stiffened perforations.***

| Beam model grade | Perforation pitch | Buckling from center to $Z$ axis (mm) | Deflection in (mm) with load in (kN) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 50 | 100 | 150 | 200 | 250 | 300 | 350 |
| M-9 | $2d$ | +100 | 4.04 | 8.08 | 12.12 | 16.17 | 20.21 | 24.24 | 28.29 |
| M-9 | $2d$ | 0 | 4.08 | 8.16 | 12.24 | 16.32 | 20.40 | 24.48 | 28.56 |
| M-9 | $2d$ | –100 | 4.11 | 8.23 | 12.35 | 16.47 | 20.59 | 24.71 | 28.82 |
| M-18 | $3d$ | +100 | 4.12 | 8.24 | 12.36 | 16.48 | 20.60 | 24.72 | 28.85 |
| M-18 | $3d$ | 0 | 4.16 | 8.33 | 12.49 | 16.66 | 20.82 | 25.00 | 29.15 |
| M-18 | $3d$ | –100 | 4.22 | 8.44 | 12.65 | 16.87 | 20.99 | 25.30 | 29.52 |
| M-27 | $4d$ | +100 | 4.12 | 8.24 | 12.36 | 16.47 | 20.59 | 24.71 | 28.83 |
| M-27 | $4d$ | 0 | 4.15 | 8.30 | 12.45 | 16.60 | 20.75 | 24.90 | 29.05 |
| M-27 | $4d$ | –100 | 4.19 | 8.34 | 12.56 | 16.75 | 20.94 | 25.13 | 29.32 |

Analyzing the data of Table 6, it can be concluded that the least deflection of beam models with diameter of the perforation of 0.5$h_w$ was obtained with the $2d$ perforations pitch. In all three cases of a different perforations pitch, the buckling of the perforation in direction of the tension or compressed flange did not significantly affect the deflection. However, it can be noted that a slight reduction in the deflection of the models is achieved by buckling the perforation in the direction of the tension beam flange. This gives grounds to state that the central part of the web is the most optimal option for the perforation location along the height of the beam web, but in cases where it is necessary to displacement the perforation, it will be more effective to displacement towards the tension flange of the beam with corrugated web.

## 4. Conclusions

The undertaken study and the obtained results lead to the following conclusions:

1. Stiffening of the web and perforation by the pair stiffeners is necessary in order to avoid local buckling under the concentrated load in the perforation zone.

2. A numerical parametric study of a beam with corrugation of triangular shape showed the efficiency of perforations location in the corrugated web with the $2d$ perforation pitch and with the diameter of the perforation of $0.25h_w$, $0.5h_w$ and $0.75h_w$ stiffened with ring plates and parallel stiffeners.

3. The reduction in deflection in all models of beams with perforations stiffened with ring stiffeners of different thickness and width, stiffeners in comparison with models without stiffening has been found.

4. The deflection reduction has been reached by using a ring stiffener with elements from the lip around the exterior circumferential edge of the ring.

5. The most effective location of the perforation along the web height has been determined, which can also be used as a guide during decision making process of beam perforations in general.

The findings showed that the optimized perforation needs to be less than half of the beam height, while the central part of the web is the most optimal option for the perforation location along the height of the beam web and most efficiency distance between the perforations is $2d$ perforation pitch.

### References


1. Bryantsev, A.A., Absimetov, V.E., Lalin, V.V. Effective application of I-beams with corrugated webs in the industrial building. Construction of Unique Buildings and Structures. 2017. No. 3 (54). Pp. 93–104.
2. Zhiyenbayeva, A.T., Khvan, K.R., Bryantsev, A.A. Historical development of corrugated beams. Actual scientific research in the modern world. 2016. No. 10-3 (18). Pp. 6–8. [Online]. URL: https://elibrary.ru/download/elibrary_27238281_29111764.pdf (date of reference: 24.11.2018).
3. Revathi, N., Satheshkumar, G.K., Arunkumar, G. Numerical investigation on flexural behaviour of cold formed steel I section with triangular corrugated web. International Journal of Research and Innovation in Engineering.2016. Vol. 02. Pp. 48–53.
4. Priyanga, R.S., Mathivathani, J., Venkatesan, A. Flexural behaviour of trapezoidal corrugation beam by varying aspect ratio. International Journal of Scientific Research Engineering & Technology (IJSRET). 2016. Vol. 4. Pp. 170–174.
5. Jager, B., Dunai, L., Kövesdi, B. Girders with trapezoidally corrugated webs subjected by combination of bending, shear and path loading. Thin-Walled Structures. 2015. Vol. 96. Pp. 227–239.
6. Sarah, A.P., Jacob, P.A. A review of optimization of plate girders with corrugated webs. International journal of Innovative Research in Science and Engineering. 2016. No. 2. Pp. 63–71.
7. Cheng, J. Summary of corrugated web H-shaped steel beam joints. International Journal of Science. 2016. Vol.3. No. 4. Pp. 136–140.
8. Hajsadeghi, M., Zirakian, T., Keyhani, A., Naderi, R., Shahmohammadi, A. Energy dissipation characteristics of steel coupling beams with corrugated webs. Journal of Constructional Steel Research. 2014. No. 101. Pp. 124–132.
9. Pavlenko, A.D., Rybakov, V.A., Pikht, A.V., Mikhailov, E.S. Non-uniform torsion of thin-walled open-section multi-span beams. Magazine of Civil Engineering. 2016. 67(7). Pp. 55–69. doi: 10.5862/MCE.67.6
10. Nazmeeva, T.V., Vatin, N.I. Numerical investigations of notched C-profile compressed members with initial imperfections. Magazine of Civil Engineering. 2016. 62(2). Pp. 92–101. doi: 10.5862/MCE.62.9
11. Hadjipantelis, N., Gardner, L., Wadee, M.A. Prestressed cold-formed steel beams: Concept and mechanical behaviour. Engineering Structures. 2018. Vol. 172. Pp. 1057–1072.
12. Soegihardjo, O., Suhardjono, S., Pramujati, B., Pramono, A.S. Parametric beam modeling to predict the first natural bending frequency of thin wall box shaped structures verified using experimental modal analysis. International Review of Mechanical Engineering. 2017. Vol. 11. No. 1. Pp. 77–86.
13. Atavin, I.V., Melnikov, B.E., Semenov, A.S., Chernysheva, N.V., Yakovleva, E.L. Influence of stiffness of node on stability and strength of thin-walled structure. Magazine of Civil Engineering. 2018. 80(4). Pp. 42–59. doi: 10.18720/MCE.80.5
14. Kikot, A.A. Design of cold-formed tension members using the CFSteel software. Magazine of Civil Engineering. 2016. 61(1). Pp. 42–59. doi: 10.5862/MCE.61.5
15. Feng, R., Zhan, H., Meng, S., Zhu, J. Experiments on H-shaped high-strength steel beams with perforated web. Engineering Structures. 2018. Vol. 172. Pp. 1057–1072.
16. De'nan, F., Hasan, H., Nassir, D. Kh., Osman, M.H., Saad, S. Finite element analysis for torsion behavior of flat web profile beam steel section with opening. Procedia Engineering. 2015. Vol.125. Pp. 1129–1134.
17. Kudryavtsev, S.V., Rogalevich, V.V. Kontsentratsiya napryazheniy vblizi krugovykh otverstiy v gofrirovannykh stenkakh balok [The stress concentration near circular holes in the corrugated webs of the beams]. Izvestiya VUZov. Stroitelstvo. 2008. No. 11. Pp. 8–13. (rus).
18. Chung, K.F. Steel beams with large web openings of various shapes and sizes: an empirical design method using a generalized moment–shear interaction curve. Journal of constructional steel research. 2003. No. 59. Pp. 1177–1200.
19. Hagen, N.C. Shear capacity of steel plate girders with large web openings, Part 1: Modeling and simulations. Journal of constructional steel research. 2009. No. 65. Pp. 142–150.

20. Shanmugan, N.E., Lian, V.T., Thevendran, V. Finite element modeling of plate girders with web openings. Thin–walled structures. 2002. No. 40. Pp. 443–464.
21. Romeijn, A., Sarkhosh, R., Hoop, H. Basic parametric study on corrugated web girders with cut outs. Journal of Constructional Steel Research. 2009. No. 65. Pp. 395–407.
22. Kiymaz, G., Coskun, E., Cosgun, C., Seckin, E. Transverse load carrying capacity of sinusoidal corrugated steel web beams with web openings. Steel and Composite Structures. 2010. No. 10 (1). Pp. 69–85.
23. Krishnan, L., Dineshraj, C.S., Prema, S. Experimental Investigation of cold-formed steel section-flexural member with triangular web. Journal of Mechanical and Civil Engineering (IOSR-JMCE). 2015. Vol. 12. Pp. 36–39.
24. Syerko, E., Diskovsky, A.A., Andrianov, I.V., Comas-Cardona, S., Binetruy, C. Corrugated beams mechanical behavior modeling by the homogenization method. International Journal of Solids and Structures. 2013. No. 50 (6). Pp. 928–936.
25. De'nan, F., Hasan, H., Choong, K. Experimental study on lateral torsional buckling of triangular web profile steel section. Applied Mechanics and Materials. 2015. Vol. 802. Pp. 178–183.
26. Pasnur, P., Kumbhare, M. Study of beam with plain web, trapezoidal corrugated web, and triangular corrugated web. Journal of Advances and Scholarly Researches in Allied Education. 2018. Vol. XV. No. 2. Pp. 630–634.
27. Maksimov, Yu.S., Ostrikov, G.M., Ibraimov, N.E. Stroitelnyie gofrirovannyie konstruktsii [Building corrugated constructions]. Almaty. 2016. 128 p. (rus)
28. International standart of Commonwealth of Independent States GOST 27772-2015 Prokat dlya stalnyih stroitelnyih konstruktsiy. Obschie tehnicheskie usloviya. [Rolled products for structural steel constructions. General specifications]. (rus)
29. Baby, A., Jacob, K. A parametric study on the effect of multi-corrugated web profile on the performance of steel beam section. International Research Journal of Advanced Engineering and Science. 2017. Vol. 2. Pp. 210–214.
30. Wang, Zh., Wang, Q., Liu, Y., Sun, M. Fatigue behaviour of welded joints assembled by longitudinal corrugated plates. Journal of Central South University. 2015. Vol. 22. Pp. 2752–2760.
31. Divahar, R., Joanna, P.S. Lateral buckling of cold formed steel beam with trapezoidal corrugated web. International Journal of Civil Engineering and Technology (IJCIET). 2014. Vol. 5. Pp. 217–225.
32. De’nan, F., Shoong, K.K., Hashim, N.S., Ken, Ch.W. Nonlinear Analysis of Triangular Web Profile Steel Section Under Bending Behaviour. Global Civil Engineering Conference. 2017. Vol. 9. Pp. 463–472.
33. Manju, T., Arundhavapriya, E., Bharath, K.B. Study on behavior of corrugated webs in cold formed steel sections with varying thickness. Asian journal of civil engineering (BHRC). 2016. Vol. 17. No. 7. pp. 1025–1033
34. Gowri, P.M., Manu, S.S. Experimental Study on Flexural Behaviour of Cold formed Hollow Flanged Z – Sections. International Research Journal of Engineering and Technology (IRJET) 2018. Vol. 05. Pp. 364–369.
35. EN 1993-1-5: Eurocode 3: Design of steel structures – Part 1–5: Plated structural elements.


### *Contacts:*


*Alexandr Bryantsev, +77779618571; Bryancev8989@mail.ru*
*Vladimir Absimetov, +77015112106; Absimetov47@mail.ru*
*Vladimir Lalin, +79213199878; vllalin@yandex.ru*


© Bryantsev, A.A., Absimetov, V.E., Lalin, V.V., 2019

Инженерно-строительный журнал

ISSN 2071-0305

сайт журнала: http://engstroy.spbstu.ru/

DOI: 10.18720/MCE.87.2

# Влияние отверстий на деформативность стенки сварной гофрированной балки

***А.А. Брянцев[a*], В.Э. Абсиметов[b], В.В. Лалин[c],***

*[a] Казахская Головная Архитектурно-Строительная Академия, г. Алматы, Республика Казахстан*

*[b] ТОО «АстанаСтройКонсалтинг», г. Астана, Казахстан*

*[c] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург*

** E-mail: Bryancev8989@mail.ru*

**Ключевые слова:** балка с гофрированной стенкой, отверстие в стенке, треугольное очертание гофр, прогиб балки, анализ методом конечных элементов, кольцевой усилитель

**Аннотация.** При проектировании некоторых объектов возникает необходимость устройства в гофрированных стенках балок отверстий различного диаметра для пропуска технологического оборудования в пределах строительной высоты балки, хотя это снижает несущую способность стенки. Отсутствие информации о характере работы, величинах критических напряжений, устойчивости гофрированных стенок балок, ослабленных отверстиями, вызвало необходимость проведения соответствующих исследований, для которых в стенках балок были образованы отверстия различного диаметра и с различными способами их подкрепления. Данное исследование, решает несколько задач: анализ работы сварных двутавровых балок с гофрированными стенками треугольного очертания, ослабленных технологическими отверстиями различного диаметра и различного расстояния между отверстиями на несущую способность; определяется влияние отверстий на способность воспринимать поперечную нагрузку, рассматриваются способы усиления отверстий. Приводится анализ влияния толщины окаймления, парных вертикальных ребер жёсткости при различной ширине кольцевого усилителя на работу моделей балок с гофрированной стенкой с отверстиями. Определено влияние загиба внешней грани кольцевого усилителя на несущую способность балок с гофрированной стенкой ослабленных отверстиями, а также наиболее эффективное месторасположение отверстия по высоте стенки, при проектировании.

## Литература

1. Bryantsev A.A., Absimetov V.E., Lalin V.V. Effective application of I-beams with corrugated webs in the industrial building // Construction of Unique Buildings and Structures. 2017. No. 3 (54). Pp. 93–104.
2. Жиенбаева А.Т., Хван К.Р., Брянцев А.А. История развития гофрированных балок // Актуальные научные исследования в современном мире. 2016. № 10-3 (18). С. 6–8.
3. Revathi N., Satheshkumar G.K., Arunkumar G. Numerical investigation on flexural behaviour of cold formed steel I section with triangular corrugated web // International Journal of Research and Innovation in Engineering. 2016. Vol. 02. Pp. 48–53.
4. Priyanga R.S., Mathivathani J., Venkatesan A. Flexural behaviour of trapezoidal corrugation beam by varying aspect ratio // International Journal of Scientific Research Engineering & Technology (IJSRET). 2016. Vol. 4. Pp. 170–174.
5. Jager B., Dunai L., Kövesdi B. Girders with trapezoidally corrugated webs subjected by combination of bending, shear and path loading // Thin-Walled Structures. 2015. Vol. 96. Pp. 227–239.
6. Sarah A.P., Jacob P.A. A review of optimization of plate girders with corrugated webs // International journal of Innovative Research in Science and Engineering. 2016. No. 2. Pp. 63–71.
7. Cheng J. Summary of corrugated web H-shaped steel beam joints // International Journal of Science. 2016. Vol.3. No. 4. Pp. 136–140.
8. Hajsadeghi M., Zirakian T., Keyhani A., Naderi R., Shahmohammadi A. Energy dissipation characteristics of steel coupling beams with corrugated webs // Journal of Constructional Steel Research. 2014. No. 101. Pp. 124–132.
9. Павленко А.Д., Рыбаков В.А., Пихт А.В., Михайлов Е.С. Стесненное кручение многопролетных тонкостенных балок открытого профиля // Инженерно-строительный журнал. 2016. № 7(67). С. 55–69. doi: 10.5862/MCE.67.6
10. Назмеева Т.В., Ватин Н.И. Численные исследования сжатых элементов из холодногнутого просечного С-профиля с учетом начальных несовершенств // Инженерно-строительный журнал. 2016. №2(62). С. 92–101. doi: 10.5862/MCE.62.9

11. Hadjipantelis N., Gardner L., Wadee M.A. Prestressed cold-formed steel beams: Concept and mechanical behaviour // Engineering Structures. 2018. Vol. 172. Pp. 1057–1072.
12. Soegihardjo O., Suhardjono S., Pramujati B., Pramono A.S. Parametric beam modeling to predict the first natural bending frequency of thin wall box shaped structures verified using experimental modal analysis // International Review of Mechanical Engineering. 2017. Vol. 11. No. 1. Pp. 77–86.
13. Атавин И.В., Мельников Б.Е., Семенов А.С., Чернышева Н.В., Яковлева Е.Л. Влияние жесткости узловых соединений на устойчивость и прочность тонкостенных конструкций // Инженерно-строительный журнал. 2018. № 4(80). С. 48–61. doi: 10.18720/MCE.80.5
14. Кикоть А.А. Расчет растянутых элементов из стальных тонкостенных холодногнутых профилей в программе CFSteel // Инженерно-строительный журнал. 2016. №1(61). С. 42–59. doi: 10.5862/MCE.61.5
15. Feng R., Zhan H., Meng S., Zhu J. Experiments on H-shaped high-strength steel beams with perforated web // Engineering Structures. 2018. Vol. 172. Pp. 1057–1072.
16. De'nan F., Hasan H., Nassir D. Kh., Osman M.H., Saad S. Finite element analysis for torsion behavior of flat web profile beam steel section with opening // Procedia Engineering. 2015. Vol.125. Pp. 1129–1134.
17. Кудрявцев С.В., Рогалевич В.В. Концентрация напряжений вблизи круговых отверстий в гофрированных стенках балок // Известия ВУЗов. Строительство. 2008. № 11. С. 8–13.
18. Chung K.F. Steel beams with large web openings of various shapes and sizes: an empirical design method using a generalized moment–shear interaction curve // Journal of constructional steel research. 2003. No. 59. Pp. 1177–1200.
19. Hagen N.C. Shear capacity of steel plate girders with large web openings, Part 1: Modeling and simulations // Journal of constructional steel research. 2009. No. 65. Pp. 142–150.
20. Shanmugan N.E., Lian V.T., Thevendran V. Finite element modeling of plate girders with web openings // Thin–walled structures. 2002. No. 40. Pp. 443–464.
21. Romeijn A., Sarkhosh R., Hoop H. Basic parametric study on corrugated web girders with cut outs // Journal of Constructional Steel Research. 2009. No. 65. Pp. 395–407.
22. Kiymaz G., Coskun, E., Cosgun C., Seckin E. Transverse load carrying capacity of sinusoidal corrugated steel web beams with web openings // Steel and Composite Structures. 2010. No. 10 (1). Pp. 69–85.
23. Krishnan L., Dineshraj C.S., Prema S. Experimental Investigation of cold-formed steel section-flexural member with triangular web // Journal of Mechanical and Civil Engineering (IOSR-JMCE). 2015. Vol. 12. Pp. 36–39.
24. Syerko E., Diskovsky A.A., Andrianov I.V., Comas-Cardona S., Binetruy C. Corrugated beams mechanical behavior modeling by the homogenization method // International Journal of Solids and Structures. 2013. No. 50 (6). Pp. 928–936.
25. De'nan F., Hasan H., Choong K. Experimental study on lateral torsional buckling of triangular web profile steel section // Applied Mechanics and Materials. 2015. Vol. 802. Pp. 178–183.
26. Pasnur P., Kumbhare M. Study of beam with plain web, trapezoidal corrugated web, and triangular corrugated web // Journal of Advances and Scholarly Researches in Allied Education. 2018. Vol. XV. No. 2. Pp. 630–634.
27. Максимов Ю.С., Остриков Г.М., Ибраимов Н.Э. Строительные гофрированные конструкции. Алматы. 2016. 128 с.
28. ГОСТ 27772 – 2015 Прокат для стальных строительных конструкций. Общие технические условия.
29. Baby A., Jacob K. A parametric study on the effect of multi-corrugated web profile on the performance of steel beam section // International Research Journal of Advanced Engineering and Science. 2017. Vol. 2. Pp. 210–214.
30. Wang Zh., Wang Q., Liu Y., Sun M. Fatigue behaviour of welded joints assembled by longitudinal corrugated plates // Journal of Central South University. 2015. Vol. 22. Pp. 2752–2760.
31. Divahar R., Joanna P.S. Lateral buckling of cold formed steel beam with trapezoidal corrugated web // International Journal of Civil Engineering and Technology (IJCIET). 2014. Vol. 5. Pp. 217–225.
32. De'nan F., Shoong K.K., Hashim N.S., Ken Ch.W. Nonlinear Analysis of Triangular Web Profile Steel Section Under Bending Behaviour // Global Civil Engineering Conference. 2017. Vol. 9. Pp. 463–472.
33. Manju T., Arundhavapriya E., Bharath K.B. Study on behavior of corrugated webs in cold formed steel sections with varying thickness // Asian journal of civil engineering (BHRC). 2016. Vol. 17. No. 7. pp. 1025–1033
34. Gowri P.M., Manu S.S. Experimental Study on Flexural Behaviour of Cold formed Hollow Flanged Z – Sections // International Research Journal of Engineering and Technology (IRJET) 2018. Vol. 05. Pp.364–369.
35. EN 1993-1-5: Eurocode 3: Design of steel structures – Part 1–5: Plated structural elements.

### *Контактные данные:*

*Александр Александрович Брянцев, +77779618571; эл. почта: Bryancev8989@mail.ru*
*Владимир Эскендерович Абсиметов, +77015112106; эл. почта: Absimetov47@mail.ru*
*Владимир Владимирович Лалин, +79213199878; эл. почта: vllalin@yandex.ru*

© Брянцев А.А., Абсиметов В.Э., Лалин В.В., 2019