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LIMIT STATE THEORETICAL AND EXPERIMENTAL INVESTIGATION OF CORRUGATED SINE-WEB UNDER PATCHLOADING

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It's presented results of the behavior and limit state investigation of thin-webbed I-beams with transversal corrugations under patch loading action. Numerical analyses via finite element method (FEM) on physical and mathematical models created according to profiles range of company Zeman and experimental investigations on two physical models with similar to them parameters and steel were executed.

At numerical investigations it was ascertained that the loss of web stability can occur both as the local form of corrugation buckling or the general buckling form for corrugations with the greater height or thickness. As the investigations result it is proved that normal stresses in the beam web under local loading reach ultimate strength of the web steel, while significant plastic strains occur in it and the bearing capacity is lost.

Keywords: corrugated web, web local stability, patch loading, buckling form, effect of patch loading parameters.

Introduction

The concept of beams with thin transverse corrugated webs to improve their stability appeared in the 1930s. Nevertheless, the problem of web-flange conjunction was resolved only in the last years with help of the modern ways of automated fabrication of structures and their welding. Nowadays, such beams are being in demand in Ukraine and through the entire world.

The current paper researches the limit state onset conditions of thin-web I-beams with transversal corrugations under patch loading.

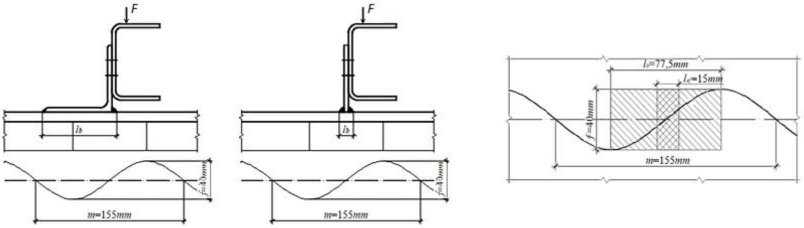
1. Web stability analysis

A numerical analytic method for calculation of local stresses in steel beam corrugated web at the level, where it joins the flange, under patch loading, is presented in [1]. The corrugated beam section stresses σ_{loc} should not be more than steel yield strength f_y according to [2, 3], that is $\sigma_{loc} \leq f_y$. The condition of non-occurrence plastic stresses was investigated in the papers [4, 5, 6, 7].

We should note, that all previously mentioned articles do not account for flange bending rigidity and shear force between flange and web, length of patch loading distribution also. Therefore, it means that results, obtained via proposed methodic by there, do not have enough scientific justification, and do not match with experimental testing, so they should be refined.

According to Broude B.M. [8], web bearing capacity does not run out reaching steel yield strength and even ultimate strength. At the same time at the level of the web and flange connection the web is crumpled.

Given article considers two types of loading application on top compression beam flange. The first type (fig. 1(a)) – the loading is applied through a purlin, welded to transversally located angles. The second (fig. 1(b)) – the loading is applied through a transversal element in the form of a strip.



(a) (b) (c)

Fig. 1. The supporting nodes of purlins on the beam with corrugated web:
(a) through angles; (b) through transversal elements; (c) load action regions

The flange width (l_b) usually is less or equal to 75…80 mm. Thus, in this paper is considered to take flange width as half of sine wave-length $\frac{m}{2} = 77.5$ mm (fig. 1(a)), and vertical element thickness as $l_b = 15$ mm (fig. 1(b), (c)).

Below is presented the results of numerical investigations via the finite elements method (FEM) of corrugated beam web limit state due to local stability loss under patch loading, distributed on the region, shown on fig. 1(c).

Local stability analysis was performed on physical and mathematical models (PMM), which had been created according to standard corrugated profiles range of company Zeman. Used profile models WTA, WTB and WTC had such geometrical parameters:

- web thickness $t_w = [2.0; 2.5; 3.0]$ mm respectively;
- web height $h_w = [500; 750; 1000; 1250; 1500]$ mm;
- flange width $b_f = 200$ mm;
- flange thickness $t_f = 8$ mm;
- f – wave amplitude with the projection length m (fig. 1)
- model length $L = 12m = 1860$ mm.

Beams were modeled by finite elements of thin shell. The mark of steel was E335 ($f_y = 305$ MPa).

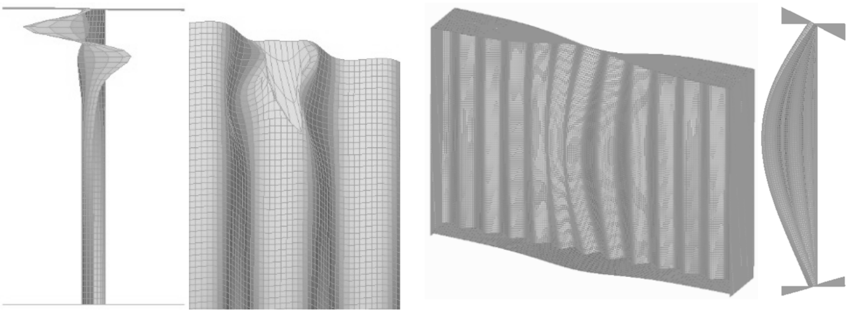
The stability calculations were performed in three stages. The 1st stage included critical stress calculations with the assumption of steel elastic behavior and geometric linearity of beam models by FEM.

In the 2nd stage, the stability analysis accounted for geometric non-linear behavior of the model and elastic behavior of steel. The results of calculations showed insignificant effect of geometric non-linear behavior account in comparison with results from previous stage (the discrepancy is less than 0.3%).

According to the 1st stage results analysis it was arranged, that critical stresses depends on web thickness,t_w, and loading distribution region length, l_b.So critical stresses increase simultaneously with the web thickness, t_w, and decrease, when l_b rises, and do not depend on the web height (table 1).

In addition, it was found two web buckling forms (fig. 2):

- Local (L) – the buckling locates on the top part of one corrugation.
- General (G) − the buckling distributes through the height of one or more corrugations.



(a) (b)

Fig. 2. (a) local buckling of corrugation; (b) general buckling of corrugation

In the local form of buckling the deformation region does not depend on the web height and thickness and starts directly under the compressed flange. The shape of this region looks crumpled (fig. 2(a)).

The form of buckling (local or general) depends on the web's slenderness ratio$\left(\lambda_w = \frac{h_w}{t_w}\right)$ (table 1) and the degree of its fixation from rotational displacements by flanges. The greater the web's slenderness ratio and less the degree of the web's edges fixation from rotational displacements by flanges the smaller the probability of general buckling form occurrence.

It is reasonable to calculate critical stresses in PMM with an accounting of plastic strains by analytic method basing on the results, got according to the linear theory and FEM.

The main parameters for webs steel is elastic module E, yieldstrengthσ_y, and proportional elastic limit $\sigma_e = 0.8\sigma_y$. Hereinafter let us use such proportion $\tau = \frac{E_t}{E}$, where E_t – tangential module, and write it in the next formula [9]:

$$\tau = \frac{(\sigma_y - \sigma_{cr})\sigma_{cr}}{(\sigma_y - \sigma_e)\sigma_e}. \tag{1}$$

Let us use the formula (1) for critical stresses calculation according to analytic method ${\sigma_{cr}}^{a}$ with plastic strains accounting [10]:

$$ {\sigma_{cr}}^{a} = \frac{Df_y}{1 + D}, \tag{2}$$

where $D = \frac{(\sigma_{cr})^2}{0.16\,\sigma_y^2}$; σ_{cr}– critical stresses, calculated by FEM with accounting elastic strains.

The critical stresses σ_{cr}^{a} values got via formula (2) are shown in table 1. As we can see, the results are insignificantly different with steel yield strength value $f_y = 305$ MPa(tolerance is less than 0.36%). At the same time, the critical stress σ_{cr} obtained via FEM for all models are exactly equal to $f_y = 305$ MPa.

Table 1

Critical stresses of local buckling in models'webs

Model	h_w, mm	l_b = 15 mm			l_b = 77,5 mm		
		Local buckling form	σ_{cr}, MPa	${\sigma_{cr}}^{a}$, MPa	Local buckling form	σ_{cr}, MPa	${\sigma_{cr}}^{a}$, MPa
WTA	500	L	2566.57	304.31	L	2042.87	303.92
	750	L	2561.30	304.31	L	2038.53	303.91
	1000	L	2575.69	304.32	L	2046.19	303.92
	1250	L	2583.86	304.32	L	2053.54	303.93
	1500	L	2588.52	304.32	L	2057.54	303.93
WTB	500	L	3720.48	304.67	L	2889.66	304.34
	750	L	3716.97	304.67	L	2879.52	304.45
	1000	L	3727.51	304.67	L	2886.38	304.46
	1250	L	3735.69	304.67	L	2893.18	304.46
	1500	G+L	3737.06	304.67	G	2485.89	304.27
WTC	500	L	5036.89	304.82	L	3831.51	304.69
	750	L	5029.48	304.83	L	3813.15	304.67
	1000	L	5040.54	304.82	L	3819.13	304.67
	1250	G+L	5034.86	304.82	G	3233.17	304.57
	1500	G	4159.87	304.74	G	2621.63	304.34

According to table results we can make conclusion, that beams with corrugated webs (by profiles range of company Zeman) will be ensured from local buckling, when web stresses by design loads are less than yield strength f_y. Such beams don't demand to install stiffening ribs.

2. Investigation of the corrugated web actual behavior

The web stability calculation by proposed above analytic method is comfortable in use, but does not an opportunity to determine a real boundary bearing capacity under local loading action. Therefore, it is important to investigate web behavior in case of its stresses significant exceeding the yield strength f_y and nearing to the ultimate strength f_u. In addition, the way of web failure should be researched.

The main purpose of the 3rd stage was investigation of real web behavior under local loading action, cross-section geometric and mechanical properties influence, and loading application schemas. As a result, it were performed numerical (on four models PMM) and experimental analysis (on two beam samples PM).

All beams were designed according to profiles range of company Zeman (table 2) with such geometric characteristics (fig. 3):

- Flange – $b_f \times t_f = 200 \times 8$ mm;
- Span – $L = 1860$ mm.

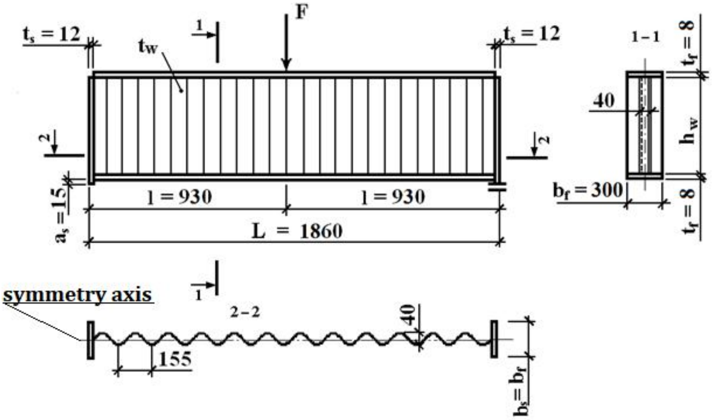


Fig. 3. Analyzed beams models schema

Table 2

	Model			
	PMM-1 / PM-1	PMM-2 / PM-2	PM-3	PM-4
h_w, mm	500	500	1000	1000
t_w, mm	3.0	3.0	2.0	3.0
l_b, mm	15.0	77.5	77.5	77.5
$F_{i,cal}$, t	14.24	20.81	14.54	20.39
$F_{i,exp}$, t	16.0	20.6	–	–

To avoid bending moment influence on bearing capacity all beams were designed with a small span.

All geometric parameters of experimented beam models (PM-1, PM-2) match with suitable analytic physical and mathematical beam models (PMM-1, PMM-2). All beams properties you can find in table 2.

Web flexibility and height influence on bearing capacity were determined via numerical investigations on additional models PMM-3 and PMM-4. Explored models had such properties:

- web thickness $t_w = [2.0; 3.0]$ mm respectively;
- web height $h_w = 1000$ mm.

Both models were loaded across the region with the length $l_b = 77.5$ mm. The research results were used for calculation of theoretical bearing capacity for the models PMM-3 and PMM-4.

The mechanical characteristics of the models' steel were got from standard samples:

- For the web – the yield strength was $\sigma_{yw} = 296.5$ MPa, the ultimate strength $\sigma_{uw} = 441.8$ MPa (sample-1);
- For the flange – the yield strength was $\sigma_{yf} = 293.9$ MPa, the ultimate strength $\sigma_{uf} = 449.2$ MPa (sample-2).

Steel behavior diagram was adopted by experimental probation of the sample-1 (fig. 4). The mechanical characteristics for analytical beam models (PMM) were taken from experimental beam models (PM).

One of the supports had the possibility to move in a horizontal direction (rolling support). Models' top flanges were fastened from horizontal movements. The sections, loaded by vertical loading, were fastened in the same way to ensure beam behavior with flat bending condition.

All PMM's were loaded in the middle of its length (fig. 1, *c*) while numerical investigation. The loading was continuously increasing with the step t (fig. 5) until bearing capacity failure. All maximum bearing capacity values of models $F_{i,cal}$, based on numerical investigations results, are shown on table 2.

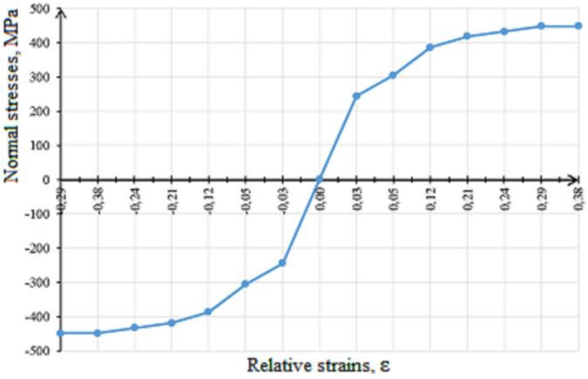


Fig. 4. Experimental diagram of steel behavior

According to normal stress to step-loading dependence diagram (fig. 5) stresses value only depends on loading distribution length l_b (curves 1, 3)and web thickness t_w (curves 2, 4) but do not depends on web height h_w (curves 3, 4).

The dependency of normal local stresses (by the loading action axis at the level of the web and flange connection) to the value of loading is shown in fig. 6(a), (b). The failure did not happen after reaching the ultimate strength f_u according to diagrams. Therefore, the web continued taking increased loading. It can be explained by that fact, that web takes stresses at the level of the web and flange connection alongside region with the length $S = 26$ mm. Moreover, these stresses do not depend on loading distribution length $l_b = 15.5$ mm or 77.5 mm. For both cases, maximum stresses are reached alongside the axis of force F application, and they decrease with deviation from this axis. After having reached the ultimate strength of the web steel σ_{uw} maximum stresses stopped increasing, but stresses, at some distance from the force F action axis, started increasing (fig. 6 (a), (b)). Therefore, the loading force reaches its maximum value.

After supporting length l_b having changed from 77.5 mm to 15 mm $\left(\frac{77.5}{15} \approx 5.17\right)$, the crashing force F decreased from 20.81 t to 14.24 t (in 1.46 times). It means that critical stresses increase when supporting length l_b decreases. That is why it is recommended to select supporting length l_b according to feasibility study.

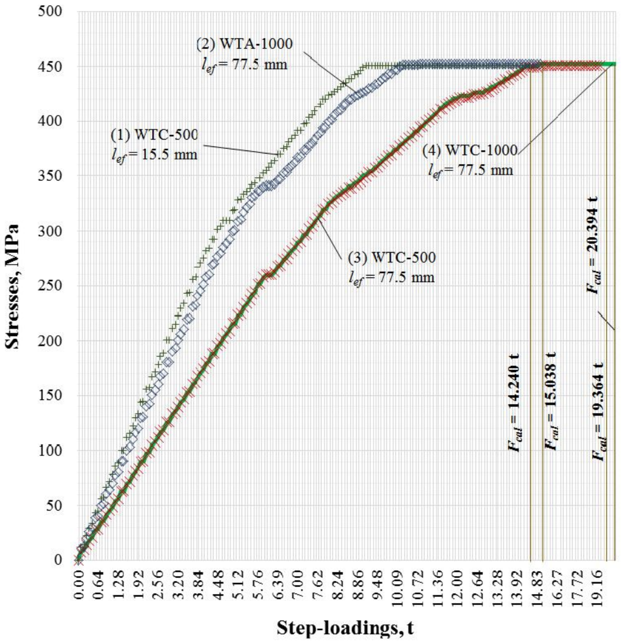
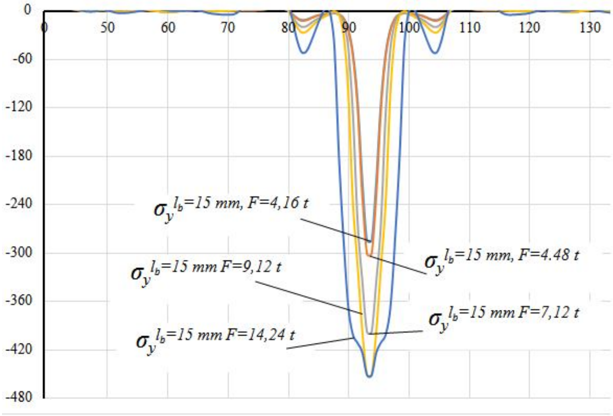


Fig. 5. Stress to step-loading dependency diagram

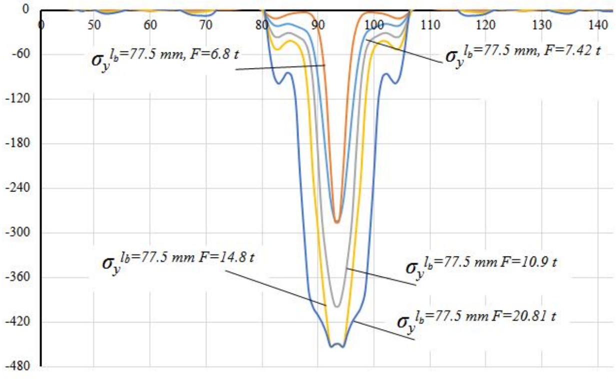
Figure 7 shows the mosaics that demonstrate the changing of web stress condition under increasing patch loading with values of loading distribution length ($l_b = 77.55$ mm and 15 mm respectively). Besides, it reflects the way of web stress change with different loadings and loading distribution lengths l_b.

Figure 7 (a) shows the stresses distribution in the section with maximum stress 398 MPa, which reached by force ($F = 10.9$ t and 7.2 t respectively). Figures 7, b and c, show the stresses distribution in the section with almost the same stresses of yield line start and end (453 MPa i 451 MPa respectively), reached by force ($F = 14.8$ t and 20.81 t respectively for b, and $F = 9.12\ t$ and 14.24 t for c).

According to numerical investigation results, bearing capacity (calculated by standard codes [2, 3]) failure, caused by patch loading, always happens earlier than web buckling, regardless of cross-section geometric parameters of corrugated beam.

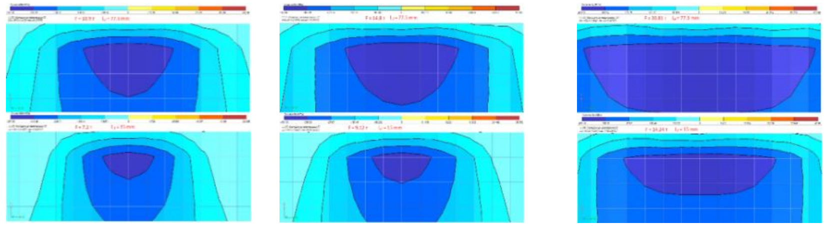


(a) $l_b = 15$ mm



(b) $l_b = 77.5$ mm

Fig. 6. Local stresses distribution diagrams with different loadings



398_MPa_77.5_398_MPa_15 start_453_MPa_77.5_451_MPa_15 end_453_MPa_77.5_451_MPa_15

(a) (b) (c)

Fig. 7. Stresses change mosaic with different loadings

The PM experimental investigation was performed in the same way to PMM numerical research. The loading was applied in the middle of beam's length by two jack-screws $Q = 2 \times 25\ t$, and was controlled by mechanical dynamometer. Reactions and deflections were noted and matched while the beam was being loaded for accurate beam behavior observing. The beams had been previously loaded until 20 kN and unloaded after some endurance for work control of jack-screws and measurement devices. Beams deflections were controlled by time type deflectometer, because of insignificant beam span value and its ratio to beam height$\left(\frac{L}{H} = \frac{1.68}{0.5} = 3.33\right)$.

The flanges were loaded through the steel filler plate with thickness 15 mm and width 300 mm (the same to flanges). The loading was distributed on the length $l_b = 15$ mm (for PM-1), and$l_b = 77.5$ mm (for PM-2).

(a) $l_b = 15$ mm (b) $l_b = 77.5$ mm

Fig. 8. The local buckling of corrugations

After having endurance, the loading was the same as in numerical investigation before bearing capacity failure with the same step (fig. 5). The limit loading value was established according to the maximum indicator of the mechanical dynamometer (table 2). The local buckling was occurring at the moment of bearing capacity failure at the level of the web and flange connection on the region, limited by corrugation half-wave length. The shape of this region looks crumpled (fig. 8).

Conclusions

According to theoretical and experimental investigations, the web bearing capacity failure and its crumpling happen, when local critical normal stresses σ_{cr} in the web (at the level of its connection with the flange under patch-loading) reach ultimate strength of the web steel σ_{uw}.

The bearing capacity of I-girders with a transversally corrugated thin web (from Zeman's profile range), under patch loading with every distribution length will be always ensured from failure if normal local stresses in the web do not exceed the steel yield strength f_y.

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Білик С.І., Лавриненко Л.І., Нілов О.О., Нілова Т.О., Семчук І.Ю.

ТЕОРЕТИЧНЕ І ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ГРАНИЧНОГО СТАНУ ПОПЕРЕЧНО-ГОФРОВАНОЇ СИНУСОЇДНОЇ СТІНКИПРИ ДІЇ ЛОКАЛЬНОГО НАВАНТАЖЕННЯ

У статті досліджується робота і граничний стан тонкостінних двотаврових балок з поперечними гофрами при локальному навантаженні. Аналіз місцевої стійкості стінки виконувався на моделях балок, які були створені відповідно до сортаменту гофрованих профілів фірми Zeman. Проводилися чисельні дослідження на фізико-математичних і експериментальні на двох фізичних моделях, подібних за параметрами і матеріалом.

Аналіз критичних напружень виконувався за методом скінченних елементів в припущенні пружної роботи сталі з врахуванням як геометричної лінійності роботи моделей, так і їх нелінійності. Розрахунок показав, що при умові пружної роботи сталі врахування геометричної нелінійності практично не впливає на результати.

Встановлено, що втрата стійкості стінки може відбуватися як за місцевою формою випинання, так і за загальною формою при більших товщинах стінки. При збільшенні довжини спирання прогонів на балку величина критичного навантаження збільшувалася, а критичні напруження в стінці зменшувалися. При цьому для всіх моделей величина критичних напружень практично не відрізнялася від межі текучості сталі f_y = 305 МПа (відхилення не більше ніж на 0,36%).

Представлені результати чисельних та експериментальних досліджень роботи гофрованої стінки при локальному навантаженні. Встановлено, що після досягнення теоретичними і експериментальними нормальними напруженнями в стінці величини межі міцності сталі несуча здатність моделі не втрачається, а руйнівне навантаження збільшується на 30-35% внаслідок перерозподілу напружень в стінці по довжині.

Результати розрахунків і експериментів свідчать, що при виконанні вимоги міцності, зазначеної Eurocode No. 3, несуча здатність гофрованої стінки буде завжди забезпеченою.

Ключові слова: гофрована стінка, місцева стійкість стінок, локальне навантаження, форма випинання, вплив параметрів навантаження.

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STRESS STRAIN STATE THEORETICAL AND EXPERIMENTAL INVESTIGATION OF CORRUGATED SINE-WEB UNDER PATCH LOADING

The article researches the behavior and limit state of thin-web bedI-beams with transversal corrugations under patch loading action. Web local stability analysis was performed on beam models, which had been created according to standard corrugated profiles range of company Zeman. Numerical analyses on physical and mathematical models and experimental investigations on two physical models with similar to them parameters and steel were executed.

The critical stress analyses were carried out via the finite elements method (FEM) with the assumption of steel elastic behavior accounting both geometric linearity and geometric nonlinearity. The calculation shows that taking into account the elastic behavior of steel the geometric nonlinearity has insignificant effect on the results.

Two buckling forms (local and general for thicker webs) were ascertained while investigating the stability loss of web. The critical loading's value increases with increasing of purlin's supporting length, but the web's critical stress decreases. But for all models critical stresses value is almost similar (tolerance is less than 0.36%) to steel yield strength f_y= 305MPa.

The numerical and experimental investigation results of corrugated web behavior under patch loading are presented. Established that model's bearing capacity does not fail after reaching by theoretical and experimental normal stresses the ultimate strength of the web steel, and ultimate loading increases by 35 – 40 % due to the stress's redistribution in the web along the length.

The results of calculations and experiments certificates that when the strength requirement specified by Eurocode No. 3 is met the corrugated web's bearing capacity will be alwaysensured.

Key words: corrugated web, web local stability, patch loading, buckling form, effect of patch loading parameters.

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ТЕОРЕТИЧЕСКОЕ И ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПРЕДЕЛЬНОГО СОСТОЯНИЯ ПОПЕРЕЧНО-ГОФРИРОВАННОЙ СИНУСОИДНОЙ СТЕНКИ ПРИ ДЕЙСТВИИ ЛОКАЛЬНОГО НАГРУЖЕНИЯ

Представлены результаты исследования работы и предельного состояния гофрированной синусоидальной стенки балки при действии локальной нагрузки. Доказано, что при действии локального нагружения нормальные напряжения в стенке балки достигают предела прочности стали стенки, при этом в ней возникают значительные пластические деформации и несущая способность исчерпывается.

Ключевые слова: гофрированная стенка, местная устойчивость стенок, локальное нагружение, форма выпучивания, влияние параметров нагружения.

УДК 624.014

Білик С.І., Лавриненко Л.І., Нілов О.О., Нілова Т.О., Семчук І.Ю. **Теоретичне і експериментальне дослідження граничного стану гофрованої синусоїдної стінки при дії локального навантаження** // Опір матеріалів і еоріяспоруд: наук.-тех. збірн. – К.: КНУБА, 2020. – Вип. 105. – С. 152-164. – Англ.

Наведені результати теоретичного і експериментального дослідження роботи і граничного стану гофрованої синусоидальної стінки при дії локального навантаження. Доведено, що нормальні напруження в стінці балки при локальному навантаженні досягають межі міцності сталі стінки, при цьому в ній виникають значні пластичні деформації і несуча здатність втрачається.

Табл. 2. Іл. 8. Бібліогр. 10 назв.

UDC624.014

Bilyk S.I., Lavrinenko L.I., Nilov O.O., Nilova T.O., Semchuk I.Y. **Limit state theoretical and experimental investigation of corrugated sine-web under patch loading** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUCA, 2020. – Issue 105. – P. 152-164.

Results obtained via limit state theoretical and experimental investigation of corrugated sine-web under patch loading action are presented. It is proved that normal stresses in the beam web under patch loading reach ultimate strength of the web steel, while significant plastic strains occur in it and the bearing capacity is lost.

Table 2. Fig. 8. Ref. 10.

УДК 624.014

Билык С.И., Лавриненко Л.И., Нилов А.А., Нилова Т.А., Семчук И.Ю. **Теоретическое и экспериментальное исследование предельного состояния гофрированной синусоидальной стенки при действии локального нагружения** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2020. – Вип. 105. – С. 152-164. – Англ.

Представлены результаты теоретического и экспериментального исследования работы и предельного состояния гофрированной синусоидальной стенки при действии локального нагружения. Доказано, что при действии локального нагружения нормальные напряжения в стенке балки достигают предела прочности стали стенки, при этом в ней возникают значительные пластические деформации и несущая способность исчерпывается.

Табл. 2. Ил. 8. Библиогр. 10 назв.

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