ISSN 1392 - 1207. MECHANIKA. 2011. 17(3): 226-231

Strength and elastic stability of cranes in aspect of new and old design standards

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crossref http://dx.doi.org/10.5755/j01.mech.17.3.495

1. Introduction

The current tendencies, connected with cranes design and the wide range of European Standardization, concerning steel construction of load – carrying structure lead to the construction of cranes (on the basis of new and more accurate calculation methods), which are lighter [1, 2] but which have lower safety margin of strength [3-5]. We can observe the development of international technical standardization, assume that the development in the domain of calculations and manufacture eliminate some dangers generated in the past. Such a philosophy was presented by the authors of new European Standards of cranes design.

In this study the FEM analysis of stability [6-8] and strength of load – carrying cranes structures, designed according to Polish Standards (PN) was carried out. The analysis was compared to the results of the same analysis according to European Standards EN 13001.

The analysis and carrying out of parametric geometrical models as a basis for FEM, were preceded by parameterization of real cranes geometrical and material constructional features according to its documentation (Fig. 1).

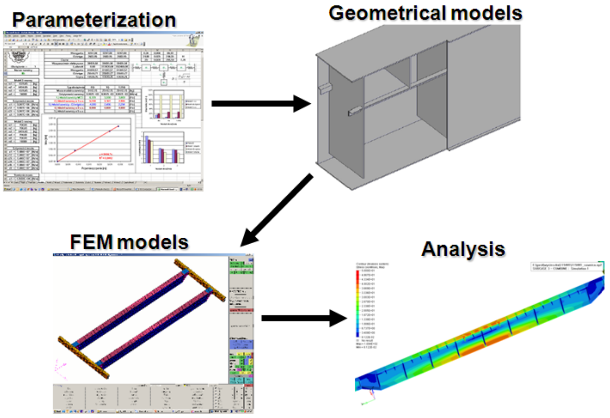

Fig. 1 General view of analysis process

2. Standardization in cranes design

At the time when design standards from eighties were obligatory [9, 10] the safety margins (reserve of stability and strength) were bigger. That caused that the designed and produced cranes according to this standards were heavier. Detailed standards provisions with ready formulas facilitated calculations of loads in the typical cases, but in other cases did not indicate the clear calculations models [11-16]. There were paradoxes in design process like very high loads assuming in some constructional details (much higher than it really was), only for not to cause stability loss of some low strength and less important elements.

The collection of new European standards of cranes design [17-19] listed different kinds of loads and proof conditions in comparison with the old standards. The loads acting on a crane are divided into the categories of regular, occasional and exceptional which shall be considered in proof against failure by uncontrolled movement, yielding, elastic instability and, where applicable, against fatigue.

Estimation of influences of new European cranes design standards on the reduction of cranes load-carrying structures mass, will be possible only after the collection of numerous number of experiences. That is the reason why from the parameter base of overhead travelling cranes with box girder [20] those with 5, 8, 12.5, 20, 35, 40 and 50 t load capacity were chosen for strength and stability calculations.

3. Analysis methodology and models preparation

The constructional features parameterisation was made on series of overhead travelling cranes, which are the dominant class of cranes used in mechanical handling. After analyzing of about 1000 cranes, more than 150 of them (designed and carried out in 1970-2005) were chosen as the representative ones. Table 1 shows basic parameters of analysed 20t hosting capacity cranes. The parameters which characterize box girder overhead travelling crane were divided into 12 groups described in detail in [20]. The analysed cranes characterise 6 forms of box girders, that depend on quantity of membranes and stiffeners (Fig. 2).

To simplify usage of parameter base and faster preparation of geometrical models a software called USPN was created (Fig. 3). It was a combination of MS Excel (Visual Basic) and Solid Edge software, which allowed the prepared for FEM calculations CAD models in only few seconds receive. For such a big base of parameters and research objects USPN was very helpful. All procedures that allow automatic generation of geometrical models were collected in this software. The application generates a 3D shell geometrical model of load-carrying crane structure parameterized in data base (MS Excel). Such a model was directly imported to FEM pre-processor (Altair Hypermesh) were finite elements model with proper boundary conditions was build. For creation of FEM model CTRIA3, CQUAD4, CHEXA, RBE2, CBAR elements and MSC,NASTRAN as the solver were used [21].

Table 1

Basic parameters of analysed 20t hosting capacity cranes

No	Hoisting capacity *Q*	Cranes span *L*	Girders span	Wheel span	Winch mass	Cranes mass	Girders width	Girders flange thickness	Web thickness	Girders height	Material
	kg	mm	mm	mm	kg	kg	mm	mm	mm	mm	
75	20000	7500	2500	4100	3985	14279	400	8	5	900	S235
76	20000	11000	3200	5100	9726	26090	500	12	6	700	S235
77	20000	13534	3300	5100	8818	35745	500	14	8	800	S235
78	20000	14000	3500	5300	6352	21764	500	12	7	700	S235
79	20000	14000	2500	4100	4183	20032	500	12	6	700	S235
80	20000	15260	5100	7700	11402	37032	560	10	7	1200	S235
81	20000	15600	2500	5000	5007	22350	400	8	6	1100	S235
82	20000	16000	4000	6500	5122	25700	550	8	7	1200	S235
83	20000	19050	3300	5850	9032	40141	550	12	7	1200	S235
84	20000	19500	3300	5850	8933	39202	550	12	8	1200	S235
85	20000	21200	2500	5000	5371	31315	650	8	6	1450	S235
86	20000	21600	6700	9800	14170	61795	650	12	7	1700	S235
87	20000	21800	2500	5000	4019	29448	650	8	7	1450	S235
88	20000	25000	3300	5850	9606	55597	650	12	8	1550	S235
89	20000	25850	3300	6100	8933	49930	650	10	7	1700	S235
90	20000	27500	3000	5600	5151	38646	650	10	7	1450	S235
91	20000	28000	4200	6750	9058	45003	650	10	7	1450	S235
92	20000	28400	5000	7800	23998	88748	650	18	7	1700	S235
93	20000	28400	5000	7800	23998	88727	650	18	7	1700	S235
94	20000	28500	5000	7800	23399	88940	650	18	7	1700	S235
95	20000	30000	7300	10100	29613	117330	700	22	7	1950	S235
96	20000	31500	5000	7800	23399	92656	650	18	7	1700	S235
97	20000	33500	5000	7800	30875	108732	700	22	7	1950	S235
98	20000	33500	2500	5100	5627	49164	650	12	7	1700	S235
99	20000	33600	3300	6400	7284	68825	700	12	8	1950	S235

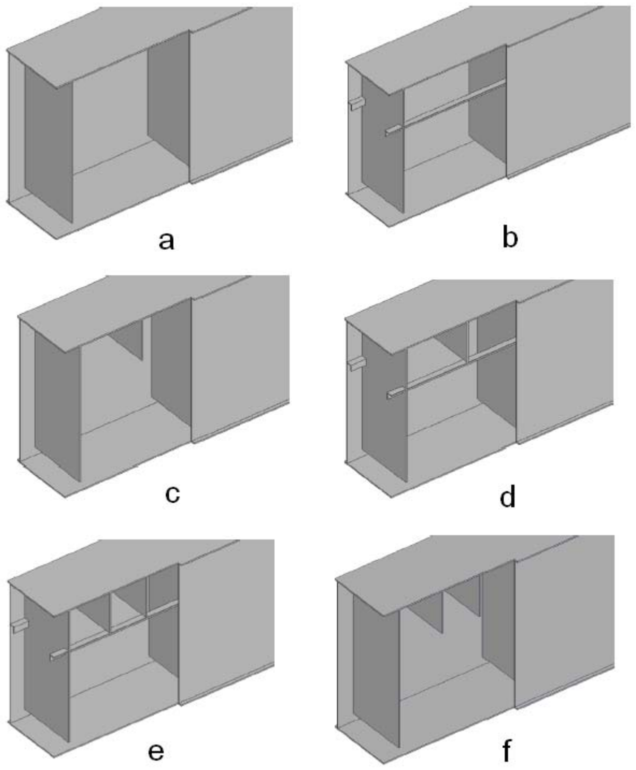

Fig. 2 Girders forms: a) 0pp + 0k; b) 0pp + 1k; c) 1pp + 0k; d) 1pp + 1k; e) 2pp + 1k; f) 2pp + 0k

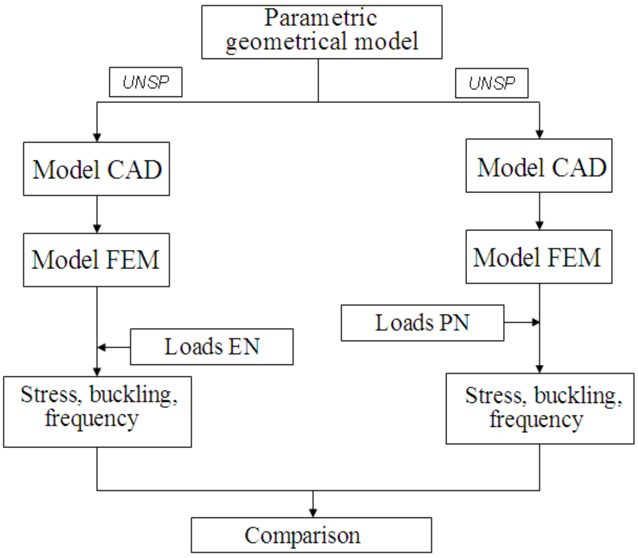

Fig. 3 Numerical research block diagram

Forces coming out from proper loads combinations were simulated as concentrated (acting on node) or as pressure. The models were supported in wheels axes. An example of crane load-carrying structure FEM model is shown in Fig. 4.

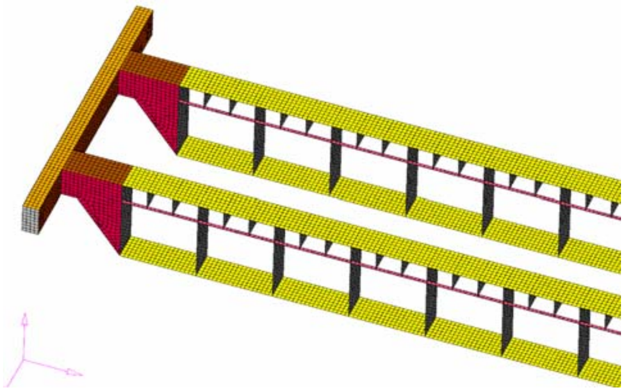

Fig. 4 FEM model of load-carrying crane structure with $Q = 5$ t and $L = 30$ m (girder 2pp + 1k with hidden web)

4. Analysis results

Strength analysis of load-carrying crane structures was carried out by calculating von Misses stress in the middle of cranes span – middle of girder was the position of hoisting winch and load (Figs. 5 and 6). Girder is the heaviest element in cranes structure, therefore decreasing its mass is more favourable than mass decreasing of other constructional details.

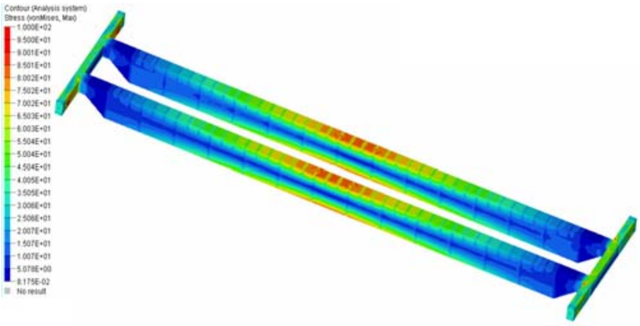

Fig. 5 Von Misses stress values for load-carrying crane structure with $Q = 20$ t and $L = 21.8$ m at A1 load combinations

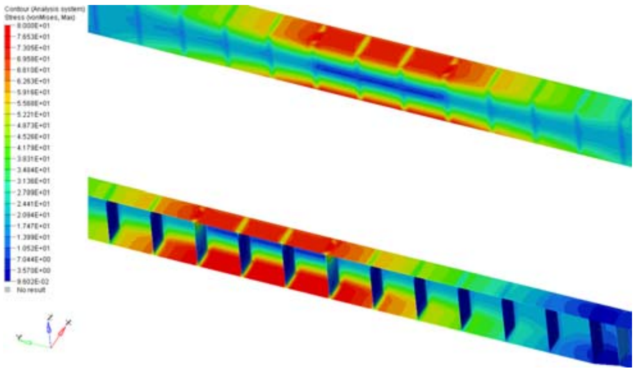

Fig. 6 Von Misses stress values for load-carrying crane structure with $Q = 12.5$ t and $L = 9$ 3 m at A4 load combinations (girder 0pp+0k with hidden web)

In analysis there was stress from load combinations according to up today used polish standards [2, 3] and new European standards calculated [4-6]. On the basis of received von Misses stresses a special W factor was calculated (separately for polish standards – W_{PN} (1) and European standards W_{EN} (2)) that could be understood as the proof of static strength degree of load-carrying crane structure. It was calculated according to

$$W_{EN} = \frac{\sigma_{EN}}{f_{Rd}} \tag{1}$$

$$W_{PN} = \frac{\sigma_{PN}}{f_{Rd}} \tag{2}$$

where f_{Rd} is limit design stress, MPa and σ is von Misses stress, MPa value for load combinations according to polish σ_{PN} or European standards σ_{EN}.

The factor W can assume values between 0 an 1. The values closer to 0 mean little proof of static strength degree of load-carrying crane structure – big overdimensioning of crane mass, however the values closer to 1 mean high proof of static strength degree of load-carrying crane structure – small overdimensioning of the crane mass. In both cases extreme values are undesirable. Comparison of W factors calculated from load combinations according to polish W_{PN} and European W_{EN} standards are shown in Figs. 7-10 (for selected hoisting capacities) and Table 2 (for cranes with 20 t hoisting capacity).

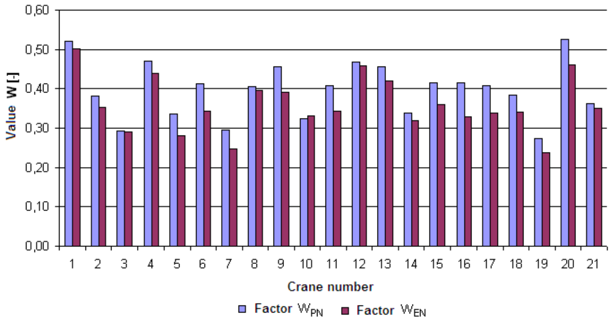

Fig. 7 Factor W values for cranes with $Q = 5$ t and $Q = 8$ t load capacities

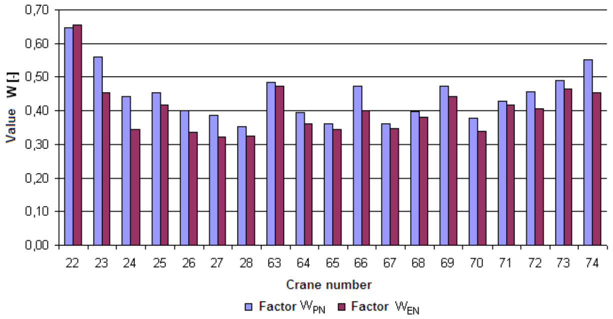

Fig. 8 Factor W values for cranes with $Q = 10$ t and $Q =$ $= 16$ t load capacities

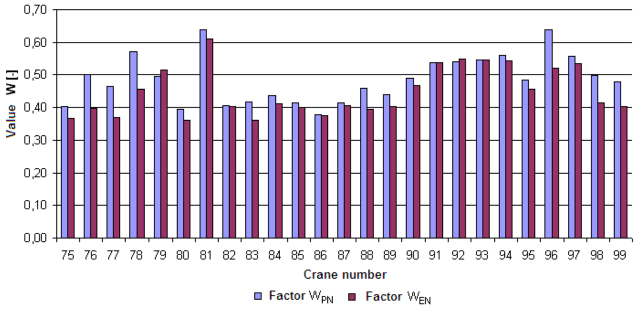

Fig. 9 Factor W values for cranes with $Q = 20$ t load capacity

Table 2

Analysis results for 20t hosting capacity cranes

No	Hoisting capacity Q	Cranes span L	Girders form	Natural frequency	Deflection q_f	Factor λ	Von Misses stress according PN σ_{PN}	Von Misses stress according EN σ_{EN}	W_{PN}	W_{EN}
	kg	mm	-	Hz	mm	-	MPa	MPa	-	-
75	20000	7500	0pp+1k	19.16	2.28	2.93	86.50	78.70	0.404	0.368
76	20000	11000	1pp+0k	7.253	7.86	3.54	107.50	85.20	0.502	0.398
77	20000	13534	0pp+0k	6.943	10.63	6.11	99.50	78.80	0.465	0.368
78	20000	14000	0pp+0k	6.879	14.79	3.85	122.20	97.60	0.571	0.456
79	20000	14000	0pp+0k	6.806	15.68	3.97	106.00	110.30	0.495	0.515
80	20000	15260	1pp+1k	6.697	7.72	3.45	84.50	77.00	0.395	0.360
81	20000	15600	0pp+1k	6.462	14.38	2.41	136.70	130.70	0.639	0.611
82	20000	16000	2pp+1k	5.780	9.23	2.83	86.80	86.20	0.406	0.403
83	20000	19050	1pp+1k	5.160	12.72	3.35	89.50	77.00	0.418	0.360
84	20000	19500	1pp+1k	5.427	13.31	4.05	93.60	87.80	0.437	0.410
85	20000	21200	2pp+1k	6.901	13.22	1.56	88.60	85.80	0.414	0.401
86	20000	21600	2pp+1k	5.816	9.57	2.33	80.80	80.20	0.378	0.375
87	20000	21800	2pp+1k	6.121	13.09	1.98	88.70	86.70	0.414	0.405
88	20000	25000	1pp+1k	4.983	14.53	2.89	98.10	84.60	0.458	0.395
89	20000	25850	2pp+1k	4.652	15.12	1.84	93.90	86.00	0.439	0.402
90	20000	27500	2pp+1k	4.132	23.25	2.11	104.90	99.80	0.490	0.466
91	20000	28000	2pp+1k	4.003	21.45	1.78	115.10	114.80	0.538	0.536
92	20000	28400	1pp+1k	3.447	19.63	1.43	110.90	112.60	0.541	0.549
93	20000	28400	1pp+1k	3.451	19.63	1.43	111.70	111.90	0.545	0.546
94	20000	28500	1pp+1k	3.427	19.57	1.45	115.00	111.50	0.561	0.544
95	20000	30000	1pp+1k	3.516	15.57	1.42	99.20	93.40	0.484	0.456
96	20000	31500	1pp+1k	2.909	26.6	1.61	130.60	106.70	0.637	0.520
97	20000	33500	1pp+1k	3.080	22.33	1.22	114.10	109.80	0.557	0.536
98	20000	33500	2pp+1k	3.514	26.11	5.28	106.70	88.80	0.499	0.415
99	20000	33600	2pp+1k	3.762	18.55	2.15	102.50	86.40	0.479	0.404

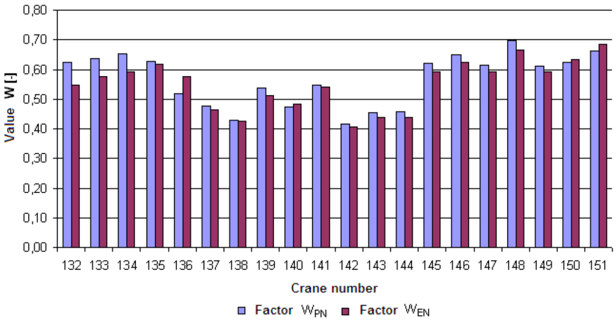

Fig. 10 Factor W values for cranes with $Q = 35$ t, $Q = 40$ t and $Q = 50$ t load capacities

Proof of elastic stability of crane elements was also made with use of FEM in case as buckling of plate fields subjected to compressive and shear stresses. The analysis was made for girders webs loaded in the middle of cranes span with maximal force coming out of hoisting capacity. The results are shown in the form of dimensionless factor λ, which is a multiplier of characteristic loads f_i – calculated from loads combinations to get critical buckling load N_K

$$N_K = f_i \, \lambda \tag{3}$$

Factor λ shows de facto "reserve" of elastic stability of load-carrying crane structure, in relation to the required value, coming out of position and loads value. An example of displacement for local stability loss – buckling of girders web is shown in Fig. 11 and factor λ values frequency for all cranes being under consideration is shown in Fig. 12.

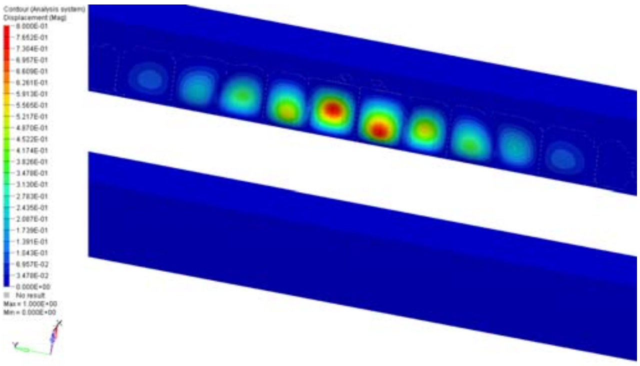

Fig. 11 Displacement for local stability loss – buckling of girders web ($Q = 50$ t; $L = 28$ m)

Additionally, as a completion of strength and stability analysis, the calculations for 10 first natural frequencies and deflection of crane structures were made. The third natural frequency was recognized as the most important one (an example is shown in Fig. 13 and values for 20 t hoisting capacity cranes in Table 2).

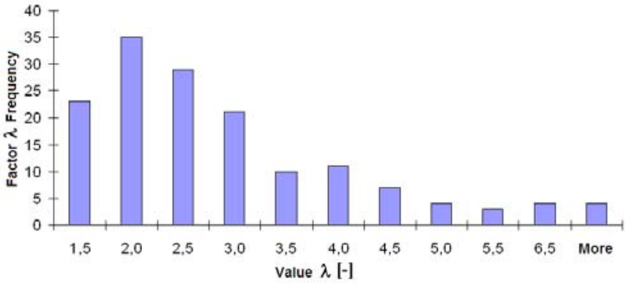

Fig. 12 Factor λ values frequency

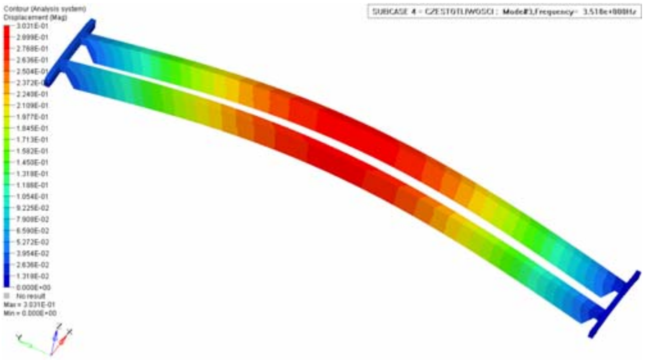

Fig. 13 Form of the third natural frequency $f = 3.518$ Hz of crane load-carrying structure ($Q = 12.5$ t; $L = 38.5$)

5. Conclusions

Analyzing the values of calculated von Misses stresses and W factors, we can observe that for majority of cranes W_{EN} factor value does not exceed 0.5. For the cranes with $Q = 5$-10 t hoisting capacity its average value is $W_{EN} = 0.37$ and increases constantly together with hoisting capacity of the crane to $W_{EN} = 0.40$ for the cranes with $Q < 20$ t, $W_{EN} = 0.50$ for $Q < 40$ t and $W_{EN} = 0.55$ for the other, W_{EN} values are less from W_{PN} in most cases. Average difference of both factors is not large and amount about 3%.

Especially for cranes with small hoisting capacity not big value of W factor could hint about overdimensioning of the structure. Of course other kind of designs proofs (especially proof of fatigue strength and proof for welded connections) are very important and it cannot be omitted, but only little girders mass decreasing could "slim" the whole load-carrying structure. Moreover, no girder form neither cranes span has an influence on factor W value.

The proof of elastic stability is made to prove that ideally straight structural members or components will not lose their stability due to lateral deformations caused solely by compressive forces or compressive stresses. This proof is retained for all structures being under consideration. The biggest values of λ factor were observed for girders types 0pp + 0k and 1pp + 0k, so those without longitudinal stiffeners. An influence of small cranes span for this girders types is significant this time. For the most common occurring girders types 1pp + 1k and 2pp + 1k, average value of λ factor becomes 2.03 and 2.66.

In comparison to proof of static strength degree (factor W), the values of factor λ becomes much higher, It shows that elastic stability reserve of load-carrying cranes structures is big. That makes potentially decreasing of the structure mass possible, through lower number of elements that do not have a special influence on strength (longitudinal or transverse stiffenings) or the application of other girders type.

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KRANŲ STIPRUMAS IR TAMPRUSIS STABILUMAS PAGAL NAUJĄ IR SENĄ PROJEKTAVIMO STANDARTUS

Rėziumė

Šiame darbe, naudojant lenkiškus standartus atliekama krūvius keliančių kranų konstrukcijos tampiojo stabilumo ir stiprumo projektavimo analizė. Šios analizės rezultatai palyginti su tokios pat analizės, atliktos pagal Europos standartus EN 13001, rezultatais. Analizuojamus kranus apibūdina šešių 6 fermų konstrukcijos, priklausomai nuo membranų ir standumo briaunų skaičiaus. Geometrinis modelis sukurtas optimalios geometrinės formos paieškai naudojant UNSP programą, BEM spręsti panaudota MSC,NASTRAN, o BEM modeliui sukurti – CTRIA3, CQUAD4, CHEXA, RBE2, CBAR elementai. Stabilumo ir stiprumo analizė atlikta keliant krūvį, kai gervė yra viduryje tarpatramio. Rezultatai pateikti bedimensine faktorių *W* ir *h* forma.

D. Gąska, C. Pypno

STRENGTH AND ELASTIC STABILITY OF CRANES IN ASPECT OF NEW AND OLD DESIGN STANDARDS

Summary

In this study the analysis of elastic stability and strength of load – carrying cranes structures, designed according to Polish Standards were carried out. The analysis was compared to the results of the same analysis according to European Standards EN 13001. The analyzed cranes characterize 6 forms of girders, depending on quantity of membranes and stiffeners. Geometrical models were created with UNSP – software carried out for better use of geometrical features base. As the FEM solver the MSC,NASTRAN was used. The elements for creation of FEM model were CTRIA3, CQUAD4, CHEXA, RBE2, CBAR. The stability and strength analysis was carried out for the case of load with hoisting capacity and hoisting winch position in the middle of a span. The results were presented in the form of dimensionless factors *W* and *λ*.

Д. Гаска, Ц. Пипно

ПРОЧНОСТЬ И УПРУГАЯ СТАБИЛЬНОСТЬ КРАНОВ ПО НОВЫМ И СТАРЫМ СТАНДАРТАМ ПРОЕКТИРОВАНИЯ

Резюме

В этой работе осуществляется анализ упругой стабильности и прочности конструкций подъемных кранов используя польские стандарты. Результаты настоящего анализа сопоставлены с результатами такого же анализа проведенного по европейским стандартам EN 13001. Рассматриваемых кранов характеризуют конструкции 6 ферм, в зависимости от числа мембран и ребер жесткости. Геометрическая модель создана по UNSP программе, использованной для поиска оптимальной геометрической формы. Для решения FEM использовано MSC,NASTRAN, а для создания элементов FEM – CTRIA3, CQUAD4, CHEXA, RBE2, CBAR, Анализ стабильности и прочности осуществлен для случая подъема груза с лебедкой в середине пролета. Результаты представлены в бездименсной форме факторов *W* и *h*.

Received November 02, 2010
Accepted May 11, 2011