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STRENGTH VERIFICATION OF ACCESSING AND RESCUE LADDER STILE

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Review article

Abstract: The article is aimed on the strength verification of accessing and rescue ladder stile under standard temperature load. Testing is performed by using manual calculation as well as computer calculation by software Autodesk Inventor 2010. The calculation is focused on the control of deflection, strain, and safety factors of ladder stile under defined load.

Keywords: Stile, ladder, deflection, strain, strength verification.

Introduction

The reason of making the above mentioned calculations was the destruction of an older type of aluminium sectional rescue ladder (see Fig. 1), which was used during the rescue operation in Rovensko pod Troskami (Hlinovsky, 2009). Doubts about proper ladder check appeared after that accident which, fortunately, resulted only with minor contusions of rescue brigade members.

Fig. 1 Ladder after destruction (Hlinovsky, 2009)

This paper presents an approximate stress analysis of stiles during ladder loading. The load is based on the standard EN 1147: 2010 Portable ladders for fire-fighters (Dufek et al., 2010). Portable ladder used at Fire Rescue units consists of four parts. It has three parts with seven rungs and one part with nine rungs. The total length of the four-part set is about 8.3 m and the total weight is about 44 kg. The ladder is made of aluminium alloy Al-Mg-Si material according to EN 6060 (Kolarik, 2007). It is designed for the intervention and rescue operations of firefighting units as a part of the equipment of fire intervention vehicle (Tauchman, 2010). No more than three people can stay on one ladder at the same time. User's control of ladders is performed according to the Methodology of the operability checking of fire equipment and material means for sectional fire ladder (Stepan, 2010).

Materials and methods

Properties of alloys Al-Mg-Si type

Alloys of aluminium with magnesium and silicon contain small amounts of manganese, iron and sometimes copper. Small amount of manganese, approximately 0.3 %, increases slightly the strength of this alloy. The higher is the manganese content in the alloy, the stronger is the effect. Magnesium content usually ranges from 0.4 to 1.2 %, exceptionally up to 1.5 wt %. The silicon is in the range from 0.4 to 1.2 wt %. The share of copper in the alloy greatly increases the alloy strength, but there is only a very small content of copper in the Al-Mg-Si types of alloys. Iron is considered adulterant, if it has a range of 0.1 to 0.5 wt %. It slightly increases the strength, softens grains and reduces recrystallization temperature (Kolarik, 2007).

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Normative safety requirements

The European Standard EN 1147:2010 Portable ladders for fire-fighters (Dufek et al., 2010) is based on the design of portable ladders for routine use by fire and rescue units and includes safety requirements. The standard specifies minimum or maximum values whereby customers can specify their own requirements. During the preparation of this standard, the fact that the tactical use of portable ladders varies in different European countries was taken into account.

The methodology of sectional ladders operability checking

The methodology (Stepan, 2010) for user's control was issued by the Ministry of Interior - General Directorate of Fire Rescue Brigade of the Czech Republic. This methodology is applied to sectional fire rescue ladders made of non-wooden materials in accordance with the standard (Dufek et al., 2010), unless the manufacturer's instructions states otherwise. The methodology describes the extent and timing of operational controls, information and recommendations for safety and examples of forms for the operational control records of sectional ladders.

Results

Methods of calculations

Two procedures were used for the stress analysis.

Variant A - Computational procedure without specialized software. Conventional procedure with knowledge of the fundamentals of statics and the strength of materials was used in calculations. The software Microsoft Office Excel 2003, Microsoft Corporation, was used. The stressed beam in its elastic part was assessed in calculations.

Variant B - calculation procedure using specialized software. An academic version of ANSYS software by the company ANSYS, Inc., was used in calculations.

The ladder made by SWS Henry Tauchman, Jilemnice (Staskova, 2009) was chosen for the strength checking of stiles. Required dimensions for the calculation issue from the total arrangement used for the deflection test (Dufek et al. 2010). The total length of the ladder l = 8235 mm (see Fig. 3) is decreased by 2 x 200 mm distance of poles from at both ends of the ladder (see Fig. 2). Section dimensions of stile profile are depicted in Fig. 4, including simplification of the profile. The weight of stile was ignored in the calculation.

Variant A

The profile was simplified in the calculation procedure without specialized software for the quadratic cross-section module deflection W_0 calculations. The profile was divided into three partial surfaces (see Fig. 4). After that the moment of inertia J_{xT} was calculated according to Steiner theorem (2). Beam deflection w was calculated from partial surfaces and their gravity centers, using the procedure described below, according to Castiglian theorem, see equation (5).

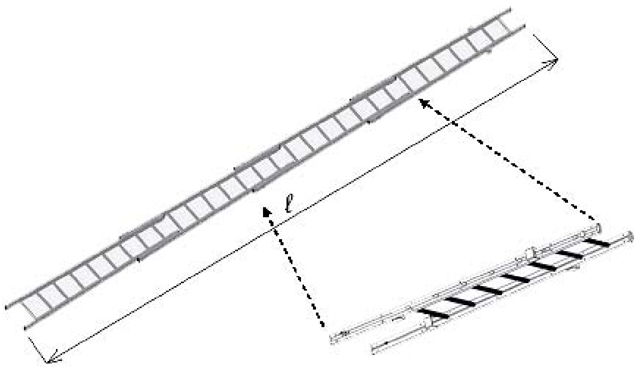

Fig. 3 Total ladder assembly and segment detail (Tauchman, 2010))

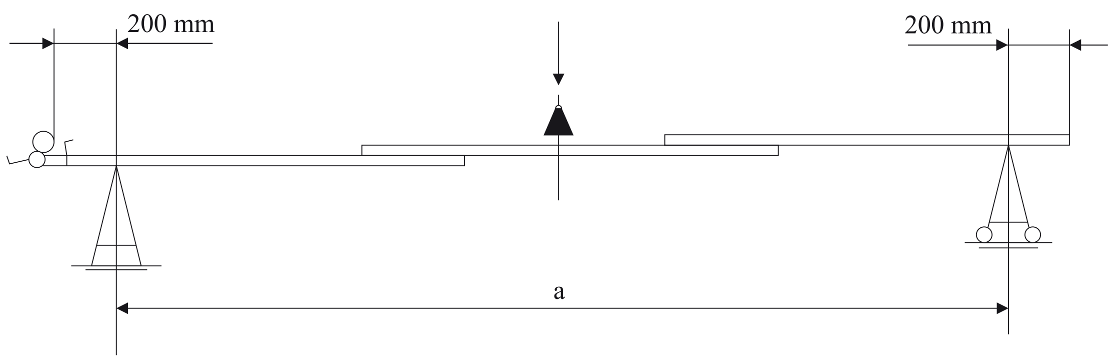

Fig. 2 Deflection test - layout (Dufek et al. 2010)

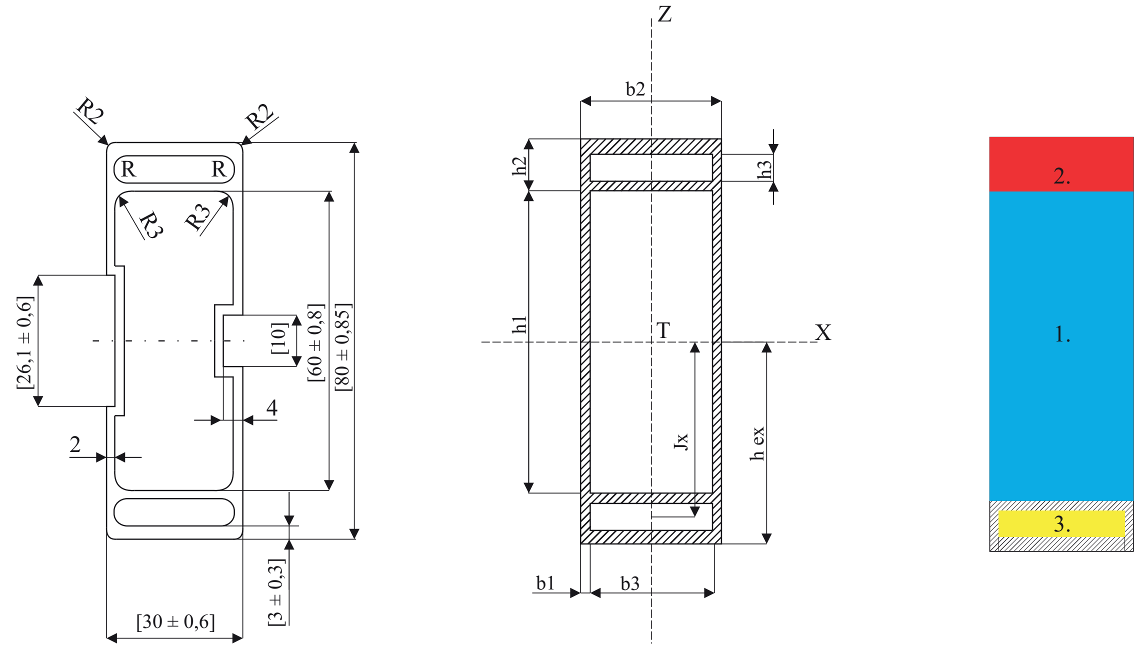

Fig. 4 The sectional view of the stile, a simplified sectional profile and partial section surface (Staskova, 2009)

Tab. 1 Input data and material properties

Dimensions [mm]		Yield strength [MPa]	
h1	60	Re	275
h2	10		
h3	5	**Ultimate strength [MPa]**	
Jx	34	Rm	310
h ex	40		
b1	2	**Young's modulus [MPa]**	
b2	30	E	68 900
b3	26		
Length [mm]			
l	7835		

Calculations were performed using equations (1) to (10). Input parameters of the profile after simplification are summarized in Tab. 1 (Kolarik, 2007).

Moment of inertia generally for the *i*-th slot:

$$J_{xTi} = \frac{b_i \cdot h_i^3}{12} \tag{1}$$

The total moment of inertia of profile J_{xT} according to Steiner theorem is calculated as the sum of the moments of inertia of the basic surface J_{xTi} and of the Steiner theorem additions, which equals the area of basic surface A_i multiplied by the square of the appropriate coordinate y_i^2 (the distance between the center of gravity of the basic surface and the center of gravity T of the total surface) according to the following equation:

$$J_{xT} = \sum J_{xTi} + \sum A_i \cdot y_i^2 \tag{2}$$

After adjustment and substitution parameters for our profile:

$$J_{xT} = 2\left(J_{xT1} + 0^2 h_1 b_1\right) + 2\left(J_{xT2} + 34^2 h_2 b_2\right) - -2\left(J_{xT3} + 34^2 h_3 b_3\right) \tag{3}$$

After modifying the expression:

$$J_{xT} = 2J_{xT1} + 2J_{xT2} + 2 \cdot 34^2 h_2 b_2 - -2J_{xT3} - 2 \cdot 34^2 h_3 b_3 \tag{4}$$

Cross-section modulus at deflection:

$$W_o = \frac{J_{xT}}{h_{ex}} \tag{5}$$

Deflection calculation according to Castiglian theorem after modifying:

$$w = \frac{1}{EJ}\int_0^{\frac{l}{2}}\left(\frac{1}{2}Fx\right)x dx = \frac{1}{EJ}\int_0^{\frac{l}{2}}\frac{1}{2}Fx^2 dx = \tag{6}$$

$$= \frac{1}{EJ}\left[\frac{1}{6}Fx^3\right]_0^{\frac{l}{2}} = \frac{1}{EJ}\left[\frac{1}{6}F\frac{l^3}{8}\right] = \frac{1}{48}\frac{1}{EJ}Fl^3$$

Bending moment of reaction F_{Ri} from the general *i*-th load:

$$M_{oi} = \frac{l}{2}F_{Ri} \tag{7}$$

Bending stress in general for the *i*-th load:

$$\sigma_{oi} = \frac{M_{oi}}{W_o} \tag{8}$$

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Safety to flexibility limit condition (MSP) generally for the *i*-th load:

$$K_{kr} = \frac{Re}{\sigma_{oi}} \quad (9)$$

Safety to strength limit condition (MSPr) generally for the *i*-th load:

$$K_{kp} = \frac{Rm}{\sigma_{oi}} \quad (10)$$

The calculation results of the above equations are summarized in Tab. 2.

Calculations of bending moments and tension in the Tab. 2 were performed for the acting forces derived from the standard load (indexes 1 and 2) and then for the load increased by 35 %, i.e. by the weights 95 kg and 142 kg (indexes 3 and 4, respectively). In addition the calculations were made for an extreme load of 200 kg (see Tab. 3). Load is considered as equally distributed on both ladder stiles. Therefore, this calculation is computed only with the force *F/2*, which bears upon one stile only.

Tab. 2 Calculated values

Section modulus in bending [mm³]		Moments of inertia [mm⁴]	
W_o	12 324	J_{xT1}	36 000
		J_{xT2}	2 500
		J_{xT3}	271
		J_{xT} total	492 958
Bending moments [Nm]		**Bending stress [MPa]**	
M_{o1}	673	σ_{o1}	55
M_{o2}	1 009	σ_{o2}	82
M_{o3}	913	σ_{o3}	74
M_{o4}	1 364	σ_{o4}	111
M_{o5}	1 922	σ_{o5}	156

Tab. 3 Input weights and corresponding acting forces

Index	Weight [kg]	Acting force F/2 [N]	Index	Weight [kg]	Acting force F/2 [N]
1	70	343	3	95	466
2	105	515	4	142	697
			5	200	981

Tab. 4 Results of calculated beam deflections and safety

Index	Deflection [mm]		Index	Deflection [mm]	
1	w_1	101,3	3	w_3	137,5
2	w_2	151,9	4	w_4	205,5
			5	w_5	289,4
Index	**Safety to MSP [-]**		**Index**	**Safety to MSP [-]**	
1	K_{kr1}	5,68	3	K_{kr3}	4,19
2	K_{kr2}	3,79	4	K_{kr4}	2,80
			5	K_{kr5}	1,99
Index	**Safety to MSPr [-]**		**Index**	**Safety to MSPr [-]**	
1	K_{kp1}	5,04	3	K_{kp3}	3,71
2	K_{kp2}	3,36	4	K_{kp4}	2,48
			5	K_{kp5}	1,76

The calculated safety coefficients K_{kpi} and K_{kri} (see Tab. 4) show that the ladder corresponds to limits of elasticity and strength under standard loads and load increased by 35 %. Even under extreme load of 200 kg, the calculated values of safety are greater than 1.

Calculated deflections have been compared according to the current testing methodology (Stepan, 2010). According to the paragraph 4.2.2.1 (Stepan, 2010), the deflection caused by load 70 kg must not exceed 2.5 % of the distance l between the poles, i.e. 196 mm. The calculated deflection w_1 = 101.3 mm lies within the allowed tolerance under the load 70 kg. The calculated deflection w_3 = 137.5 mm is satisfactory for the load increased by 35 % to 95 kg.

According to the paragraph 4.2.2.2 (Stepan, 2010), the deflection caused by the load 105 kg must not exceed 1.5 times the deflection calculated according to the paragraph 4.2.2.1, i.e. 159 mm. Calculated deflection w_2 = 151.9 mm corresponds to the tolerance under load up to 105 kg. Calculated deflection w_4 = 205.5 mm after the increasing of normalized load by 35 % to 142 kg does not meet the standardized value.

If the calculation result from the increased load deflection, i.e., w_3 = 137.5 mm, was used as a base, then the 1.5 multiple makes 206.3 mm, and therefore the deflection will be just below the limit value. The deflection w_5 = 289.4 mm exceeds both limits under the extreme load 200 kg.

Variant B

Software based on the finite element method (FEM) was used for the calculations. Several variations of FEM model of ladder stile section were prepared with different meshes and types of finite elements. Optimal and computationally most stable

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version of three-dimensional model for structural analysis was made from 20-nodes elements SOLID 186. This option was chosen for the follow-up studies and will be described further. The model consists of 117 177 finite elements with 224 558 nodes. For computations, the linear isotropy material model was used.

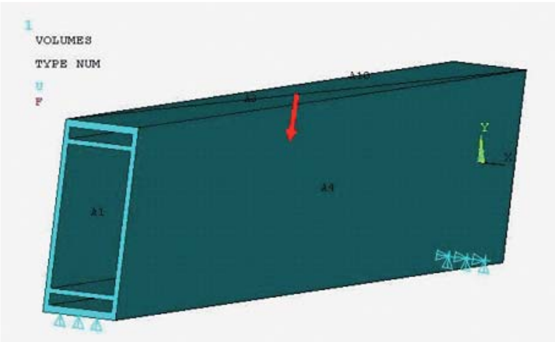

Fig. 5 Cross-section of ladder stile, boundary conditions and load of the model

The length of 3D finite-element model of tension stile section was specified as 7835 mm. The beam was loaded in the middle by single force (Fig. 5). In the first stage, such a configuration of boundary conditions was chosen, so that the model corresponded to a simple beam; it corresponded to hinge bearing at both ends of the profile.

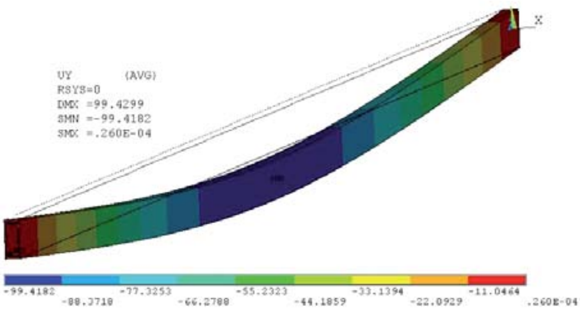

Fig. 6 Deflection of the ladder stile w

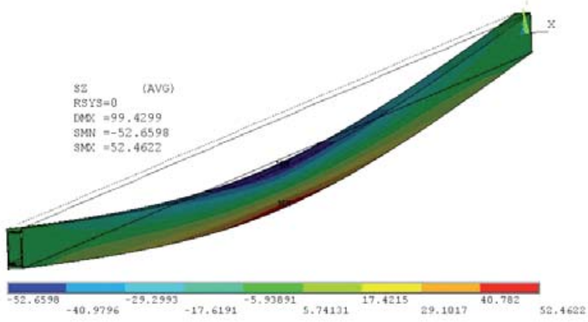

Fig. 7 Stress σ_z on the ladder stile

Results of the analysis are deflections of stile section and maximum stress values. Fig. 6 and 7 show graphical visualization of deflection and stress σ_z for the first numerical model (343 N).

Final values of deflections and stresses for single load cases (see Tab. 3) are presented in Tab. 5 and 6.

Tab. 5 Results of calculated deflections of ladder stile according to FEM

Index	Deflection [mm]		Index	Deflection [mm]	
1	w_1	99,4	3	w_3	135,1
2	w_2	149,3	4	w_4	202,0
			5	w_5	284,4

Tab. 6 Results of calculated stresses of the ladder stile according to FEM

Index	Stress σ_z [MPa]		Index	Stress σ_z [MPa]	
1	σ_{o1}	52,5	3	σ_{o3}	71,5
2	σ_{o2}	79,1	4	σ_{o4}	107,0
			5	σ_{o5}	150,6

Discussion

Two methods were used for the simulation of ladder load calculations. It is evident from manually calculated results, that both standardized and increased by 35 % loads are above elasticity and strength limits. The value of safety coefficient is higher than one. Extreme loading does not meet the safety standards. Results of calculated deflection were compared according to the methodology (Stepan, 2010). Results are within the suitable tolerance only under the loads 70 and 95 kg at in situation when deflection must not exceed 2.5 % of the ladder length. During the test, when the load must not exceed 1.5 multiple of deflection detected in the first calculation, only the load 105 kg is suitable.

Unfortunately, the 3D model had to be simplified for software computation, which resulted in forces distribution that did not correspond to the real situation. The software calculated with the load acting only on a half of the beam, without considering the effects of the other half. Therefore, these results cannot be compared to the manual calculations, where the beam is taken as a whole. For the load of 105 kg, the result of a deflection based on the analysis on Fig. 7, presents the value of 173 mm.

Tab. 7 The results of checking records on the operability of sectional ladders at the Fire District of Ostrava, for the year 2010

Measured values	a	7940	7950	7950	7940	7940	7940
	A	1113	1113	1141	1118	1129	1124
	B	954	948	986	955	964	960
	C	882	868	910	880	883	893
	D	1115	1111	1139	1117	1130	1124
Calculated values	b = 2,5 % a	198,5	198,8	198,8	198,5	198,5	198,5
	c = 1,5(A-B)	238,5	247,5	232,5	244,5	247,5	246
	A-B	159	165	155	163	165	164
	A-C	231	245	231	238	246	231
	A-D	-2	2	2	1	-1	0
Registered number		0581	2228	9430	6411	7201	3640

The results acquired from checking records on the operability of sectional ladders at Fire brigades of Moravian - Silesian Region through the year 2010 according to the methodology (Stepan, 2010) and archived at the Fire District of Ostrava are presented in the Tab. 7 for the comparison with the real 4-part ladder assembly deflection. The real deflected ladder was another type then that the one used for the calculations. The type of ladder had the code 5021, produced by Hymer - Leichtmetallbau GmbH & Co.KG, Wangen, Germany. Nevertheless, the ladder has the same technical parameters as for loading limit and operational designation for rescue action (intervention). Measured differences of values A-B represent deflections w_1 from the load 70 kg. Deflections vary around the average value 162 mm. Measured differences of values A-C represent deflections w_2 from the load 105 kg. Deflections get around the average value 237 mm.

Calculated data should be verified by 3D modeling and by the strength analysis at the different professional graphic system, e.g. Pro/ENGINEER, by PTC Company, Needham, USA. Definitive verification of theoretic calculations and computer models should be made by measuring the deflections of a real ladder, using strain gauges.

Conclusion

Calculations confirm that standardized tests are within safety limits of used material. We did not expect any other result.

However, these results do not solve the problem of exceeding strength limits due to any other reasons (e.g. improper location of the ladder according to the technical conditions set by producers, exposition to inadequate strokes or oscillations, exceeding heat effects and using in abnormal ways). In the past, when wooden ladders were used, cracking noise had appeared before the destruction. Extended heat effects became evident as the changes of color. Aluminium, as more fragile material than steel, goes relatively quickly from the yield limit to the strength limit under the tensile stress, without any marked warning by the size of relative stretching.

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