Experimentální Analýza Napětí 2010
Experimental Stress Analysis

Experimental and numerical analysis of failure in press supporting structure

František Trebuňa,[1] František Šimčák,[2] Jozef Bocko,[3] Peter Trebuňa,[4] Patrik Šarga[5]

Abstract: After almost ten years of operation of a press that was used for forming of instrument housing erose cracks on tree vertical columns of press. Analysis of failure causes in a frame of press provided by numerical and experimental methods of mechanics has formed a base for the steps recommended in order to ensure further operation without failure. Analysis has shown that the basic design principles are violated also today and together with inperfections in material (sulphide) in location of concentrators the failure became reallity.

Keywords: Press supporting structure, Crack initiation, Experimental methods

1. Introduction

After approximately ten years of operation of a press (Fig.1) used for cutting and forming of side panels of washing machines, there were detected transversal cracks in vertical columns of press frame (Fig.2). They reach 30-40% of their cross-sections. The press with maximal projected force of a ram 3500 kN was equipped with an automatic limiter of maximal loading force.

With respect to operational conditions it was necessary operatively analyze causes of crack initiation in columns of press frame and on the base of such analysis to suggest the measures in order to ensure its further failure-free operation. The aim of a paper is to present results that have been reached during solution of this problem.

[1] *Dr.h.c. mult. prof. Ing. František Trebuňa, CSc.; Department of mechanics and mechatronics at Faculty of mechanical engineering at Technical University of Košice; Letná 9, 042 00 Košice, Slovak republic; frantisek.trebuna@tuke.sk*

[2] *prof. Ing. František Šimčák, CSc.; Department of mechanics and mechatronics at Faculty of mechanical engineering at Technical University of Košice; Letná 9, 042 00 Košice, Slovak republic; frantisek.simcak@tuke.sk*

[3] *doc. Ing. Jozef Bocko, CSc.; Department of mechanics and mechatronics at Faculty of mechanical engineering at Technical University of Košice; Letná 9, 042 00 Košice, Slovak republic; jozef.bocko@tuke.sk*

[4] *Ing. Peter Trebuňa, PhD; Department of mechanics and mechatronics at Faculty of mechanical engineering at Technical University of Košice; Letná 9, 042 00 Košice, Slovak republic; peter.trebuna@tuke.sk*

[5] *Ing. Patrik Šarga, PhD; Department of mechanics and mechatronics at Faculty of mechanical engineering at Technical University of Košice; Letná 9, 042 00 Košice, Slovak republic; patrik.sarga@tuke.sk*

Fig. 1. View of the press.

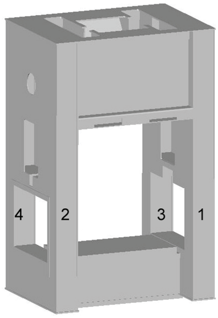


Fig. 2. Computational model of press frame.

2. Description of press failure

Design of press frame is apparent from computational model for application of finite element method given in Fig.2.

During press operation are accomplished simultaneously two operations in one working cycle (one ram stroke of the press)

- cutting from a sheet of rectangle shape,
- forming of cutted piece from previous operation.

From the analysis of loading of individual operations was according to [3] found out that maximal load acting to press ram is $F_s = 1800$ kN during cutting and $F_o = 1200$ kN during forming, i.e. for simultaneous execution of both operations the maximum force acting to press ram reaches 3000 kN. According to data gained from the operator, the press force limiter was adjusted to the magnitude of force in interval 3200 kN to 3500 kN during the whole period of its previous operation. Despite of above-mentioned fact there were detected cracks in three columns of the press approximately after ten years of operation (with approximately $8 \cdot 10^6$ working cycles). In Fig.3 are seen to more details locations and shapes of cracks in bottom parts of columns No. 1, 2 and 4.

As results from presented figure, the cracks were initiated in three columns and they were localized in bottom part of press frame in locations of transition of columns to bottom crossbeams of press frame. The columns have closed rectangular cross-section created from sheets according to Fig.4 and the cracks were spread through whole thickness of sheets that form the column walls. As results from inspection of crack lengths, the carrying cross-sections of columns were decreased by 30 to 40% by cracks.

Subsequent inspection detected further cracks in press frame. These have local character and they affected small part of supporting structure and they were probably initiated after creation of cracks in press columns.

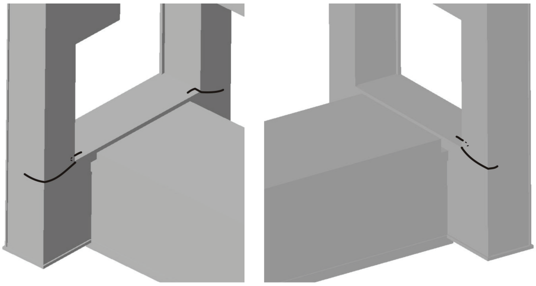


Fig. 3. The cracks in bottom part of press frame columns.

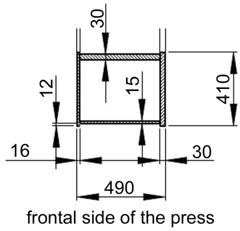


Fig. 4. Cross-section of column No. 2.

Material properties of press frame were accomplished by tensile test in correspondence with STN 100 002+AC1 with test specimen of dimensions $d_0 = 8$mm, $\ell_0 = 40$ mm. From the test result the following values: R_{eH} = 376 MPa, R_{eL} = 343 MPa, R_m = 499 MPa, $A_5 = 31{,}7\%$; Z = 67,3%.

3. Determination of residual stresses in frame columns by the hole-drilling method

For the measurement of residual strains was used hole-drilling equipment RS-200 [7,9] and self-compensating strain-gages 1-RY-21-3/120 with *k*-factor 2,06 on all grids. The strain-gages were applied by strain-gage glue X60 and protective silicon coat SG-250. Location and orientation of strain-gages on columns of press frame is apparent from Fig.5.

As results from Fig.5, the strain-gages were applied in the neighborhood of cracks on inner walls of columns with the aim to gain better knowledge about residual stress levels in observed areas. Measurement was performed with strain-gage rosettes with radius 5,15 mm and the diameter of drilled hole was 3,21 mm. Depth of drilled hole was 5 mm and the drilling was accomplished in ten steps, each with length of 0,5 mm.

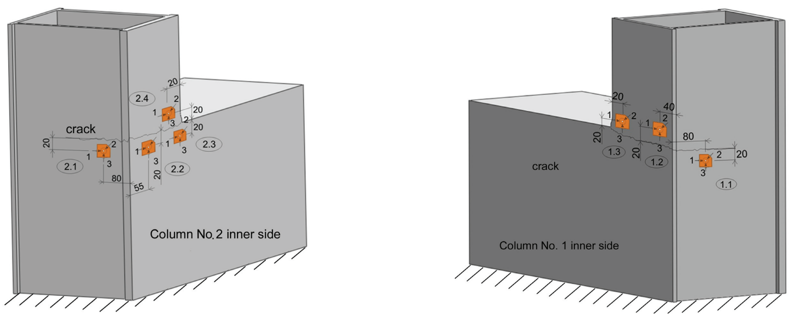


Fig. 5. Locations of strain-gages on columns No. 1 and 2 of press frame.

The magnitudes of residual stresses were determined according to standard ASTM E 837-01 [1] as well as by Integral method and method of Power-Series. For the measurement of strains released during drilling was used strain-gage apparatus P3 [11]. In Table 1 are given magnitudes and directions of residual stresses determined according to ASTM E-837-01.

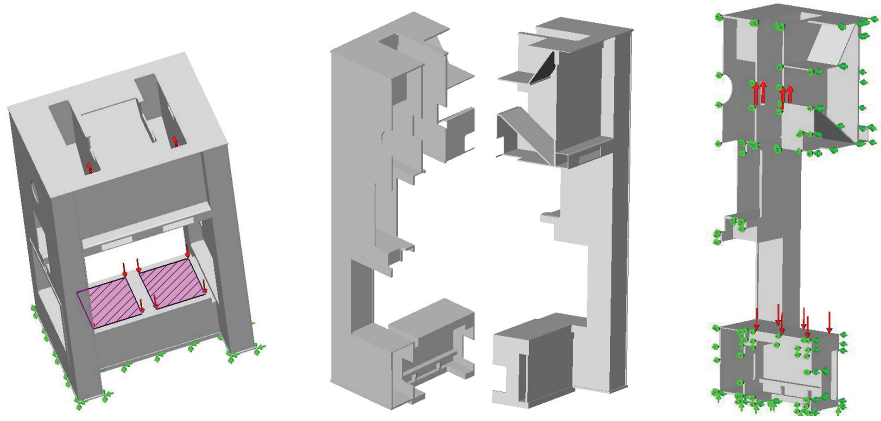
Table 1. Values of residual stresses and their directions according to ASTM E-837-01

Location of measurement	Column No.1			Column No.2		
	σ_{max} [MPa]	σ_{min} [MPa]	φ [°]	σ_{max} [MPa]	σ_{min} [MPa]	φ [°]
X.1	16,42	-61,10	18,86	6,46	-56,84	2,12
X.2	31,25	5,52	52,21	26,02	13,73	-77,57
X.3	37,21	13,97	27,73	28,33	15,05	-75,85
X.4	-	-	-	20,19	4,45	-15,61

Annotation: X=1,2 is a column number.

4. Stress analysis of press frame by the finite element method

In Fig.6a is a press frame model together with boundary conditions applied for numerical solution. Hatching marks the places on which are applied technological forces acting on bottom part of frame. On the left side is a force of cutting, on the right side a force of forming. Reaction forces are transmitted through a ram to crank mechanism in upper part of press frame.



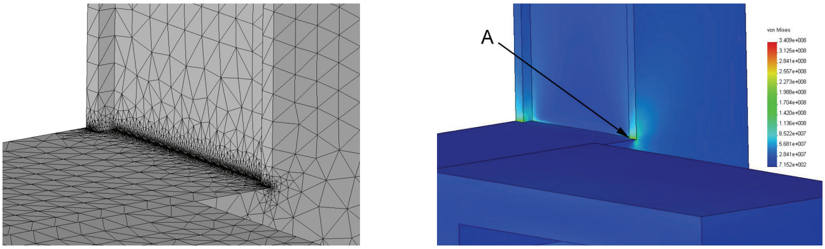
a) b) c)

Fig. 6. Model of press frame. a) whole frame with boundary conditions, b) quarter-press model, c) boundary conditions for quarter-press model.

Computation was realized for a whole loading force in ram 3500 kN (maximal allowable force determined by force limiter). This force was divided to two parts: 2100 kN for cutting and 1400 kN for forming. In order to identify stress concentrators in locations of cracks there was utilized geometrical symmetry of the frame and the computations were performed on the quarter, more loaded part of frame (Fig.6b). This increased precision of computation by application of smaller finite elements in critical part and at the same time it decreased time of computations. Boundary conditions according to Fig.6c supposed symmetrical loading of the press, which represents adverse state of loading in comparison with a real state.

In Fig.7a is a detail of mesh in the area of cracks (junction of column to bottom crossbeam). Stress concentration in this location is apparent from the field of equivalent stresses in Fig.7b. In this computation was considered sharp corner (without rounding) in the junction of column to crossbeam.

As results from the stress analysis, the maximum equivalent stresses in the area of question marked by capitol letter A, reach the value 273 MPa.



a) **b)**

Fig. 7. Location of junction between column and bottom crossbeam. a) meshed model, b) the field of equivalent stresses.

5. Discussion of possible reasons of cracks initiation in press frame

Computed values of residual stresses determined from measured strains released by drilling on inner sides of column walls did not exceed 40 MPa (see Table 1). All values are positive, i.e. they support growth of cracks. Their magnitudes on sidewalls lie in interval 20 - 40 MPa that clearly documents fact that they were not produced during manufacturing of frame. It can be supposed that they result from loading during operation of press. With respect to their magnitudes they can not be considered as direct reasons of cracks initiation, because during the operation of the press is invoked vanishing loading for which the middle stress is equal to halve of stress amplitude. From the numerical computation of press frame by the finite element method results that in the junction of frame column with bottom crossbeam (location A in Fig.7b) is located extreme stress concentration with maximal equivalent stress 273 MPa. Maximal stress is initiated on inner wall side with thickness 30 mm in the location of sharp (not rounded) corner.

For determination of critical upper stress level for vanishing cycle and fatigue of material is according to [8,10] used value 0,61.Rm for vanishing tension and 0,74.Rm for vanishing bending. Here, Rm is the strength of material. With respect to the facts confirmed by numerical computation, the bending stress in columns caused by different stiffness of columns and crossbeams as well as resulting due to eccentric loading during working cycle has very small level. Consequently, most tensile loading influences the critical stress value, i.e. the critical stress for vanishing loading can be determined from the formula 0,61.Rm. For a determined strength of materials this corresponds to upper stress level approximately 300 MPa.

As we see, even with considering stress concentration in the corner without rounding, the magnitude of maximal equivalent stress is smaller than the upper critical value of material from which the column is made. Exceeding of upper critical stress can occur only in case of non-anticipated force increasing (e.g. tight pull of the cutting) and non-functional force limiter. This should result to forces that exceed 3500 kN.

The second reason of crack formation can be proneness of material to crack initiation. In order to verify this possibility there were realized tests of material toughness by Charpy hammer in accordance with STN EN 100 E45-1, STN EN 875. For the test was used pendulum hammer PSW 300.

The realized test has shown that the magnitudes of fracture energy KV lie in interval 77 J - 115 J and magnitudes of notch toughness KCV in interval 96 J/cm^2 – 144 J/cm^2.

According to STN 73 1401, the recommended magnitudes of impact toughness are connected with yield stress and the factor that influences desired magnitude is also type of loading, i.e. it is different for static and dynamic loading. For the steel materials with yield stress with maximum 275 MPa and dynamical loading is required notch toughness KCV=50 J/cm^2.

For the materials with yield stress with maximum 355 MPa is required notch toughness 70 J/cm^2 [4,5]. Notch toughness measured from test specimens exceeds the values given in standard.

In Fig.8 are given shapes of fracture surfaces gained from two impact tests. In the fracture surfaces of both specimens are apparent rolled out inclusions that substantially influenced test results. If these are found in two specimens, it can be stated that this fact significantly influences behavior of press frame and it can initiate crack for small stress amplitude levels. As it is evident from fracture surface in Fig.8, the percentage of brittle fracture is close to 50%.

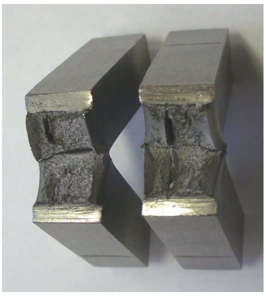


Fig. 8. Fracture surfaces of specimens for evaluation of toughness.

Measurement was accomplished at temperature 20ºC. It is evident that there exists hazard of brittle fracture, because material is in a state near to transit area and for the temperatures under 20ºC the danger of brittle fracture is real.

From the analysis of results follows that the cracks in the structure of press frame arose in sharp corners of junction of press columns and bottom crossbeams and they were probably caused by inappropriate geometry of press frame and low purity of material. For the analysis of press frame strengthening, in order to ensure further operation of press without failures, was used the finite element method. The stress analysis by the FEM has shown that rounding of corner with radius 40 mm in locations of junction of steel sheets on columns with bottom crossbeams (location A Fig.7b) decreases maximal value of equivalent stresses from 273 MPa to 180 MPa, i.e. by approximately 35%.

On the base of above-mentioned facts was suggested to provide (after welding of cracks) strengthening of press frame by welding eight plates made of material S355 to all columns (one on inner and outer side of each column). The shapes of plates are given in [12]. As results from computations realized for press frame with strenghtening the maximal equivalent stresses in critical locations did not exceed 190 MPa.

6. Conclusions

On the base of numerical and experimental analysis of press frame can be stated:

- Numerical analysis of press frame has shown that occurrence of sharp corners (without rounding) in the junction of columns and bottom crossbeams causes (in case of maximal allowable loading of ram 3500 kN) equivalent stresses 273 MPa.
- The levels of residual stresses in press frame columns did not exceed, according to ASTM E 837-01, absolute value 62 MPa. The stress levels on sidewalls of columns did not exceed 40 MPa and they lie in interval 20 to 40 MPa. Residual stresses on frontal walls of columns did not exceed in its absolute value level 62 MPa and these stresses were invoked by operation of press.
- Crack initiation in inner corners of columns (location A, Fig.7b), and also in other locations can be, with the most probability, caused by overloading during operation. This did not occur during ordinary technological process of pressing (cutting and forming), but as a result of inappropriate position of semi-finished product and accordingly to formation of additional forces during movement of ram. However, this case has to be connected with infunctionality of force limiter.
- Another possible reason of cracks initiation is low purity of press frame material that is documented by probably rolled out sulphides and consequently occurs lamellar splitting of material.

- Strengthening of bottom parts of columns by welded plates will result to decreasing of maximal equivalent stresses by approximately 30%, which is enough for further safe operation of press.
- In order to eliminate possible press frame overloading the author have suggested providing calibration of press limiter and its regularly checking.

Acknowledgement

The authors acknowledge by project VEGA 1/0004/08.

References

[1] ASTM E 837-01. *Standard Test Method for Determining Residual Stresses by the Hole Drilling Strain-Gage Method* (New York, 2001).

[2] Fürbacher I., Macek K., Steidl J. a kol., *Lexikon technických materiálů* (VERLAG DASHÖFER, 2005). ISBN 80-86229-02-5.

[3] Hrivňák A. a kol., *Technológia plošného tvárnenia* (Alfa, Bratislava, 1989).

[4] STN 73 1401. Juhas P. a kol., *Navrhovanie oceľových konštrukcií* (SÚTN, Marec, 1998).

[5] Juhas P., *Spoľahlivosť a pevnosť materiálových oceľových konštrukcií* (ELFA, Košice, 2009).

[6] Kobayashi A.S., *Handbook on Experimental Mechanics* (VCH Publishers, Cambridge, 1993).

[7] Redner S. and Perry C.C., "Factors Affecting the Accuracy of Residual Stress Measurements Using the Blind Hole Drilling Method," in *Proceedings of 7th International Conference Experimental Stress Analysis*, Haifa, Israel, August 1982 (1982), pp. 604-616.

[8] Trebuňa F. and Buršák M., *Medzné stavy – lomy* (Grafotlač, Prešov, 2002). ISBN 80-7165-362-4.

[9] Trebuňa F. and Šimčák, F., *Kvantifikácia zvyškových napätí tenzometrickými metódami* (GRAFOTLAČ, Prešov, 2005). ISBN 8080732272.

[10] Trebuňa F. and Šimčák F., *Odolnosť prvkov mechanických sústav* (Emilena, TU SjF Košice, 2004). ISBN 80-8073-148-9.

[11] Trebuňa F. and Šimčák F., *Príručka experimentálnej mechaniky* (TYPOPRESS, Košice, 2007). ISBN 970-80-8073-816-7.

[12] Trebuňa F. a kol., Návrh úprav stojana lisu manzoni za účelom vykonania jeho opráv s cieľom ďalšieho prevádzkovania. (TU Košice, December, 2009).