387. INVESTIGATION OF COMPRESSION OF ELEMENTS OF PACKAGING MATERIALS

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Abstract. A one-dimensional model for the analysis of compression of a paper in the printing machine is presented. It is assumed that a paper experiences static compression and the problem of initial stability is solved. A two-dimensional model for the analysis of compression of a paper is described and used for the solution of a similar problem. Also an axi-symmetric model for the analysis of compression of a paper is described and used for the solution of a similar problem.

A setup for performing experimental investigations of uniaxial unidirectional symmetrically distributed compression of polymeric film is designed and created. For this purpose the method of digital speckle photography is used. During the investigations the images of the stability eigenmodes of the polymeric film HDPE for uniaxial unidirectional compression of the film were determined.

The obtained results are used in the design of the elements of the printing machine.

Keywords: paper, polymeric film, compression, experimental setup, speckle photography, image processing, correlation analysis, stability, eigenmode, printing machine, finite elements, axi-symmetric problem.

Introduction

The analysis of stability of a paper in the printing machine is based on the relationships described in [1, 2].

The one-dimensional model for the analysis of paper stability in the printing machine is based on the analysis of beam bending. Thus the analysis consists of two stages:

1) The static problem of longitudinal motion of a bar is solved, assuming that the longitudinal displacements at the ends of the analyzed paper are given;
2) stability of the investigated paper as of a beam with additional stiffness due to the static compression determined in the previous stage of analysis is analyzed (the first stability eigenmodes are determined).

The two-dimensional model for the analysis of paper stability in the printing machine is based on the analysis of plate bending. Thus the analysis consists of two stages:

1) the static problem of the plane stress is solved, assuming the displacements at the edges of the analyzed paper are given;
2) stability of the investigated paper as of a plate with additional stiffness due to the static compression determined in the previous stage of analysis is analyzed.

The axi-symmetric model for the analysis of paper stability in the printing machine is based on the analysis of an axi-symmetric elastic structure. Thus the analysis consists of two stages:

1) the static problem is solved, assuming the displacements at the edges of the analyzed structure are given;
2) stability of the investigated structure because of the additional stiffness due to the static compression determined in the previous stage of analysis is investigated.

Optical methods find wide application for the investigation of mechanical characteristics: moire methods (shadow moire [3], geometric moire [4], plotting of circular moire fringes for the visualisation of certain types of dynamic processes [5], stochastic moire for the identification of plane vibrations [6]) and the methods of speckle photography [7] and interferometry [8].

A great number of investigations of mechanical characteristics of the materials used in poligraphy and packaging technology (paper, cardboard, polymeric and multilayered combined materials) are performed worldwide [9, 10]. When performing investigations, usually tension experiments are performed, and from the analysis of the obtained data conclusions about the mechanical characteristics of the materials are made. But the number of papers in which the behaviour of materials and products used in polygraphy in the process of compression is investigated is rather low. Thus because of the mentioned reasons this research is considered to be important.

In paper [11] the vibrations of the paper tape are investigated for the given loading of the paper tape. In this paper the method of digital speckle photography is used for the analysis of uniaxial unidirectional symmetrically distributed compression of the materials used in polygraphy.

The obtained results are used in the process of design of the printing machine elements.

One-dimensional model for the analysis of paper stability in the printing machine

Further x, y and z denote the axes of the orthogonal Cartesian system of coordinates. First the static problem of longitudinal motion of a bar is analyzed. The element has one nodal degree of freedom: the displacement u in the direction of the x axis. The stiffness matrix has the form:

$$[K] = \int [B]^T \left[\frac{E}{1-\nu^2} h \right] [B] dx, \tag{1}$$

where E is the modulus of elasticity, ν is the Poisson's ratio, h is the thickness of the paper and:

$$[B] = \left[\frac{dN_1}{dx} \quad \ldots \right], \tag{2}$$

where N_i are the shape functions of the finite element.

It is assumed that the longitudinal displacements at the ends of the analyzed paper are given and they produce the loading vector $\{F\}$. Thus the vector of displacements $\{\delta\}$ is determined by solving the system of linear algebraic equations:

$$[K]\{\delta\} = \{F\}. \tag{3}$$

In the second stage of the analysis the eigenproblem of stability of the beam with additional stiffness due to the static longitudinal compression is solved. The beam bending element has two nodal degrees of freedom: the displacement w in the direction of the z axis and the rotation Θ_y about the y axis. The displacement due to bending u in the direction of the x axis is expressed as $u=z\Theta_y$.

The stiffness matrix has the form:

$$[\overline{K}] = \int \begin{pmatrix} [\overline{B}]^T \left[\frac{E}{1-\nu^2} \frac{h^3}{12} \right] [\overline{B}] + \\ + [\hat{B}]^T \left[\frac{E}{2(1+\nu)1.2} h \right] [\hat{B}] \end{pmatrix} dx, \tag{4}$$

where:

$$[\overline{B}] = \left[0 \quad \frac{dN_1}{dx} \quad \ldots \right], \tag{5}$$

$$[\hat{B}] = \left[\frac{dN_1}{dx} \quad N_1 \quad \ldots \right]. \tag{6}$$

The matrix of additional stiffness has the form:

$$[\overline{K}_\sigma] = \int [G]^T [M][G] dx, \tag{7}$$

where:

$$[G] = \left[\frac{dN_1}{dx} \quad 0 \quad \ldots \right], \tag{8}$$

$$[M] = \left[\frac{E}{1-\nu^2} h \right] [B]\{\delta\}. \tag{9}$$

The i-th critical value of the loading parameter λ_i and the corresponding stability eigenmode $\{\delta_i\}$ are determined from:

$$\left([\overline{K}] + \lambda_i [\overline{K}_\sigma]\right)\{\delta_i\} = \{0\}. \tag{10}$$

Results of the analysis of the paper stability in the printing machine using the one-dimensional model

For the static problem of longitudinal motion of a bar the following boundary conditions are assumed: at the left end the longitudinal displacement is assumed to be equal to zero, while at the right end it is assumed to be given a prescribed negative value. For the problem of transverse vibrations at both ends, both generalized displacements are assumed equal to zero.

The first eigenmode of stability is presented in Fig. 1, the second eigenmode of stability is presented in Fig. 2, …, the tenth eigenmode of stability is presented in Fig. 10.

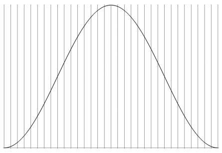

Fig. 1. The first stability eigenmode.

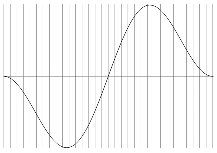

Fig. 2. The second stability eigenmode.

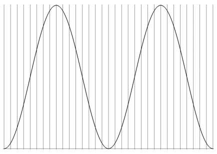

Fig. 3. The third stability eigenmode.

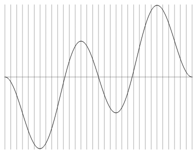

Fig. 4. The fourth stability eigenmode.

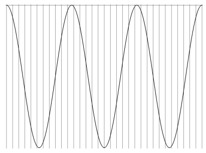

Fig. 5. The fifth stability eigenmode.

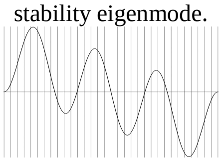

Fig. 6. The sixth stability eigenmode.

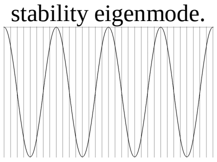

Fig. 7. The seventh stability eigenmode.

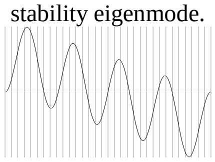

Fig. 8. The eighth stability eigenmode.

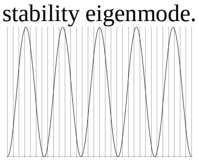

Fig. 9. The ninth stability eigenmode.

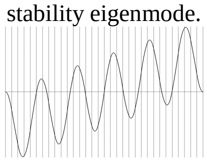

Fig. 10. The tenth stability eigenmode.

Experimental investigation of a polymeric film compression

In the printing machines of roll type when transporting the polymeric film between separate printing sections, the uniaxial unidirectional compression of the tape of polymeric film may take place because of different velocities in different printing sections, the effect of temperature (the layer of paint which is located on the surface of the tape is dryed after each printing section) and because of other reasons (Fig. 11).

In order to take the effect of the possible uniaxial compressive loading of the flexible polymeric tape into account when the printing material is transported in the printing machine and when the loading is symmetric, the experimental setup for the digital speckle photography investigations was designed and produced (Fig. 12). For the symmetric loading of the film tape, the compressive load was distributed symmetrically with respect to the center line of the tape of the polymeric film by loading both of its sides with equal compressive load q.

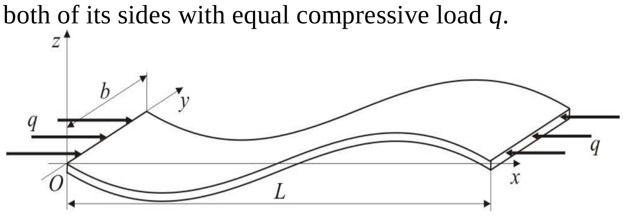

Fig. 11. Principal scheme of the motion of the tape of polymeric film in the printing machine and of the compression between separate printing sections: b – width of the polymeric film, L – length of the film, q – compression loading

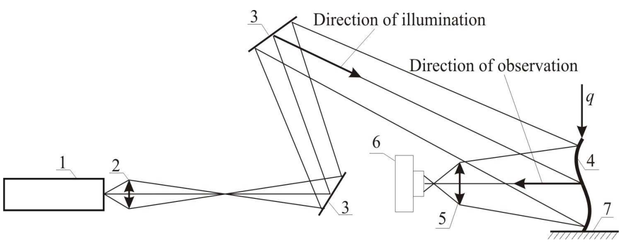

Fig. 12. Experimental setup for the digital speckle photography investigations designed for the analysis of the effect of the compressive loading of the tape of polymeric film: 1 – *He-Ne* laser, 2 – expanding lens, 3 – mirrors, 4 – the investigated polymeric material, 5 – focusing lens of the digital image camera, 6 – digital image camera, 7 – the base, q – the load

The surface of the polymeric film was illuminated with coherent monohromatic light using the Helium–Neon laser (HN-40, corresponding to IEC 825-1:1993). This laser generates the light beam with the wavelength λ = 632,8 nm (part of the spectrum of the red colour seen by an eye). The main parameters and characteristics of the laser and of the power source are presented in Table 1.

Table 1

The main parameters and characteristics of the laser HN-40 and of the power source

Parameter		**Value**
Parameters of the laser	Radiated wavelength	632.8 nm
	Maximum power	39 mW
	Polarisation	1000:1
	Diameter of the beam	2.1 (±0,1) mm
	Expansion	2.1 mrad
Conditions of operation	Operating temperature	10 – 40 ^{o}C
	Humidity of air	≤ 93 %
Allowable values of voltage at 50Hz	Not less than	198 V
	Not more than	242 V

The laser beam was expanded by using the expansion lens and directed to the side of the investigated tape of polymeric material by using the system of mirrors. The polymeric tape was deformed by loading it with load q , and because of this the tape was deformed and definite speckle images occured. By changing the load the shapes of the obtained speckle images varied. At definite values of loads the images of the stability eigenmodes occured.

Speckle images were registered with the high resolution colour digital image camera Edmund Optics EO-1312C USB Camera. Each photo was registered with the time interval of 40 ms. The quality of the photo did not change when changing the time interval between the registrations. The main characteristics of the image camera are presented in Table 2.

Table 2

The main technical characteristics of the image camera Edmund Optics EO-1312C USB Camera

Model	EO-1312C USB Camera
Sensor Type	1/2" Progressive Scan CMOS
Pixels (H x V)	1280 x 1024
Pixel Size (H x V)	5.2 µm x 5.2 µm
Sensing Area (H x V)	6.6 mm x 5.3 mm
Pixel Depth	8-bitm
Frame Rate	25 fps
Resolution	>100 lp/mm image space resolution 50% @ F4, 400 mm WD (18 mm FL meets 100 lp/mm with max 2/3" CCD)
Distortion	<0.3% @ 400mm WD <1% @ 400mm WD for 18 mm FL
Shutter Type	Rolling
Lens Mount	C-Mount
Sync System	Internal or Via Software
Camera/Exposure Control	Via Software
Dimensions (WxHxL)	34 x 32 x 27.4 mm

Focusing lens Edmund Industrial Optics 55326 Double Gauss Focuss 25 mm was used with the videocamera, which has the lens of wide viewing field and variable aperture. The main characteristics of the focusing lens are presented in Table 3.

Table 3

The main characteristics of the focusing lens Edmund Industrial Optics 55326 Double Gauss Focuss 25 mm

Focal Length	**25 mm**	
	Min.	**Max.**
Primary Mag	0.106 X	∞
FOV (2/3" CCD Hor)	87.5 mm	20.7°
FOV (1/2" CCD Hor)	63.6 mm	15.1°
Resolution in Object Space (1/2" CCD)	11 lp/mm	N/A
Working Distance	240 mm	∞
Aperture (f/#)	F4 - closed	
Distance to First Lens	21.4~24.1 mm	
Filter Thread	M 30.5 x 0.5 mm	

The camera transferred the obtained images to the personal computer through the USB 2.0 connection where the obtained images were processed with the specialised software uc480viewer (version 2.40.0005) and their correlation analysis was performed.

In Figures 13, 14, 15 and 16, the images of the stability eigenmodes of the polymeric film HDPE (dimensions L = 200 mm, b = 200 mm) are presented for uniaxial unidirectional compression of the film.

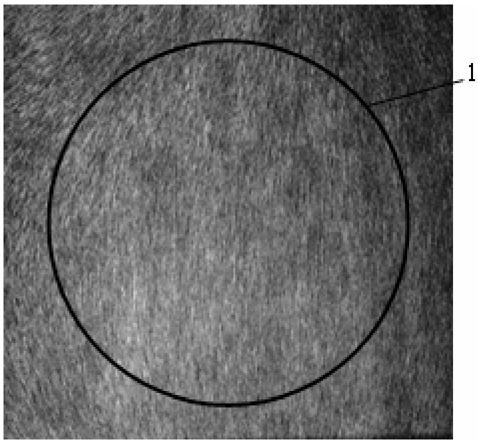

Fig. 13. Image of the first stability eigenmode of the polymeric film HDPE for uniaxial unidirectional compression of the film: loading 0.88 N, deformation 55 µm, 1 – shape of first stability eigenmode

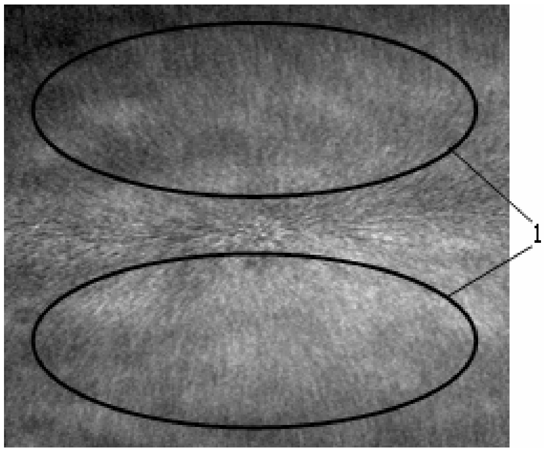

Fig. 14. Image of the second stability eigenmode of the polymeric film HDPE for uniaxial unidirectional compression of the film: loading 1.47 N, deformation 21 µm, 1 – shape of second stability eigenmode

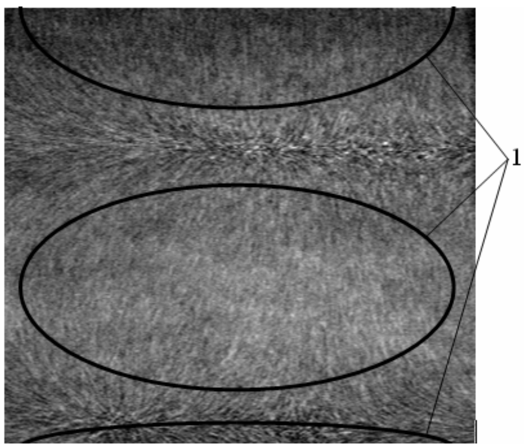

Fig. 15. Image of the third stability eigenmode of the polymeric film HDPE for uniaxial unidirectional compression of the film: loading 2.45 N, deformation 13 µm, 1 – shape of third stability eigenmode

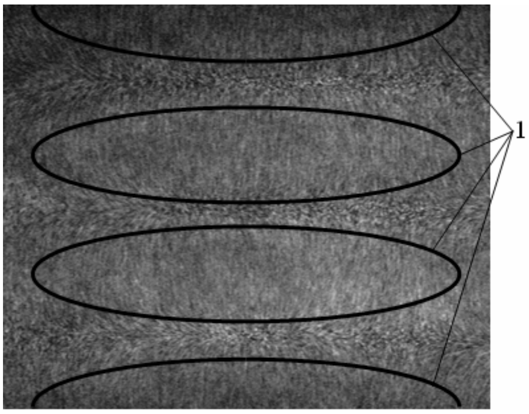

Fig. 16. Image of the fourth stability eigenmode of the polymeric film HDPE for uniaxial unidirectional compression of the film: loading 3.14 N, deformation 10 μm, 1 – shape of fourth stability eigenmode

From Figures 13, 14, 15 and 16, one can see that with the increase of the uniaxial unidirectional load images of the stability eigenmodes change. First, when loading the film, one large peak forms in its central part (maximum deformation of 55 μm takes place when the load is 0,88 N). By further increase of the load one can observe varying speckle images and the second, third and fourth stability eigenmodes occur. With further increase of the load, speckle images are located non uniformly and it is difficult to identify the eigenmodes. Also one can note that with the increase of the load the change of deformations is negative.

Two-dimensional model for the analysis of paper stability in the printing machine

Further x, y and z denote the axes of the orthogonal Cartesian system of coordinates. First, the static problem of plane stress is analyzed. The element has two nodal degrees of freedom: the displacements u and v in the directions of the axes x and y of the orthogonal Cartesian system of coordinates.

It is assumed that the displacements at the boundary of the analyzed paper are given and they produce the loading vector. Thus the vector of displacements is determined by solving the system of linear algebraic equations.

In the second stage of the analysis the eigenproblem of stability of the plate with additional stiffness due to the static compression in the plane of the paper is solved. The element has three nodal degrees of freedom: the transverse displacement of the paper w and the rotations Θ_x and Θ_y about the axes of coordinates x and y. The displacements due to bending u and v in the directions of the axes x and y are expressed as $u=z\Theta_y$ and $v=-z\Theta_x$.

The stiffness matrix has the form:

$$[\overline{K}] = \int \left([\overline{B}]^T [\overline{D}][\overline{B}] + [\overline{\overline{B}}]^T [\overline{\overline{D}}][\overline{\overline{B}}] \right) dxdy, \qquad (11)$$

where:

$$[\overline{B}] = \begin{bmatrix} 0 & 0 & \frac{\partial N_1}{\partial x} & \dots \\ 0 & -\frac{\partial N_1}{\partial y} & 0 & \dots \\ 0 & -\frac{\partial N_1}{\partial x} & \frac{\partial N_1}{\partial y} & \dots \end{bmatrix}, \qquad (12)$$

where N_i are the shape functions of the finite element and:

$$[\overline{D}] = \frac{h^3}{12} \begin{bmatrix} \frac{E}{1-\nu^2} & \frac{E\nu}{1-\nu^2} & 0 \\ \frac{E\nu}{1-\nu^2} & \frac{E}{1-\nu^2} & 0 \\ 0 & 0 & \frac{E}{2(1+\nu)} \end{bmatrix}, \qquad (13)$$

where h is the thickness of the paper, E is the modulus of elasticity and ν is the Poisson's ratio and:

$$[\overline{\overline{B}}] = \begin{bmatrix} \frac{\partial N_1}{\partial y} & -N_1 & 0 & \dots \\ \frac{\partial N_1}{\partial x} & 0 & N_1 & \dots \end{bmatrix}, \qquad (14)$$

$$[\overline{\overline{D}}] = \frac{Eh}{2(1+\nu)1.2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \qquad (15)$$

The matrix of additional stiffness has the form:

$$[\overline{K}_\sigma] = \int [G]^T [M][G] dxdy, \qquad (16)$$

where:

$$[G] = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & 0 & \dots \\ \frac{\partial N_1}{\partial y} & 0 & 0 & \dots \end{bmatrix}, \qquad (17)$$

$$[M] = h \begin{bmatrix} \sigma_x & \tau_{xy} \\ \tau_{xy} & \sigma_y \end{bmatrix}, \qquad (18)$$

where the stresses σ_x, σ_y, τ_{xy} are determined from the static problem of plane stress.

Results of analysis of paper stability in the printing machine using the two-dimensional model

A square piece of paper is analyzed. For the static problem of plane stress the following boundary conditions are assumed: on the lower boundary $u=v=0$, on the upper boundary $u=0$ and $v=-1$, on the left and the right boundaries $u=0$. For the problem of plate bending on the lower and the upper boundaries all the generalized displacements are assumed equal to zero.

Contour plot for the first eigenmode of stability is presented in Fig. 17, for the second eigenmode of stability is presented in Fig. 18, …, for the ninth eigenmode of stability is presented in Fig. 25.

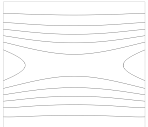

Fig. 17. The first stability eigenmode

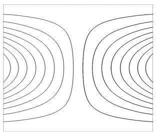

Fig. 18. The second stability eigenmode

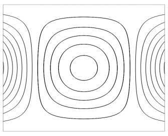

Fig. 19. The third stability eigenmode

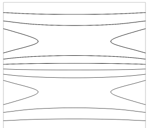

Fig. 20. The fourth stability eigenmode

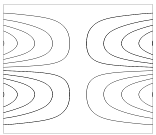

Fig. 21. The fifth stability eigenmode

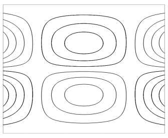

Fig. 22. The sixth stability eigenmode

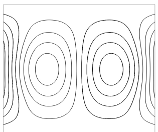

Fig. 23. The seventh stability eigenmode

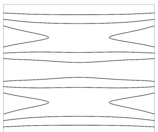

Fig. 24. The eighth stability eigenmode

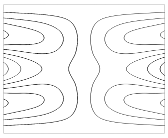

Fig. 25. The ninth stability eigenmode

Axi-symmetric model for the analysis of stability of the paper in the elements of packages

Further x denotes the radial coordinate and y denotes the axial coordinate of the cylindrical system of coordinates. First, the static problem is analyzed. The element has two nodal degrees of freedom: the displacements u and v in the directions of the axes x and y described previously.

It is assumed that the displacements at the boundary of the analyzed structure are given and they produce the loading vector. Thus the vector of displacements $\{\delta\}$ is determined by solving the system of linear algebraic equations.

In the second stage of the analysis the eigenproblem of stability of the structure with additional stiffness due to the static compression is solved.

The stiffness matrix has the form:

$$[K] = \int [B]^T [D][B] 2\pi x dx dy, \tag{19}$$

where:

$$[B] = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & \dots \\ 0 & \frac{\partial N_1}{\partial y} & \dots \\ \frac{N_1}{x} & 0 & \dots \\ \frac{\partial N_1}{\partial y} & \frac{\partial N_1}{\partial x} & \dots \end{bmatrix}, \tag{20}$$

where N_i are the shape functions of the finite element and:

$$[D] = \begin{bmatrix} K+\frac{4}{3}G & K-\frac{2}{3}G & K-\frac{2}{3}G & 0 \\ K-\frac{2}{3}G & K+\frac{4}{3}G & K-\frac{2}{3}G & 0 \\ K-\frac{2}{3}G & K-\frac{2}{3}G & K+\frac{4}{3}G & 0 \\ 0 & 0 & 0 & G \end{bmatrix}, \tag{21}$$

where:

$$K = \frac{E}{3(1-2\nu)}, \tag{22}$$

$$G = \frac{E}{2(1+\nu)}, \tag{23}$$

where E is the modulus of elasticity and ν is the Poisson's ratio.

The matrix of additional stiffness has the form:

$$[K_\sigma] = \int [G]^T [M][G] 2\pi x dx dy, \tag{24}$$

where:

$$[G] = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & \dots \\ 0 & \frac{\partial N_1}{\partial x} & \dots \\ \frac{\partial N_1}{\partial y} & 0 & \dots \\ 0 & \frac{\partial N_1}{\partial y} & \dots \\ \frac{N_1}{x} & 0 & \dots \end{bmatrix}, \tag{25}$$

$$[M] = \begin{bmatrix} \sigma_x & 0 & \tau_{xy} & 0 & 0 \\ 0 & \sigma_x & 0 & \tau_{xy} & 0 \\ \tau_{xy} & 0 & \sigma_y & 0 & 0 \\ 0 & \tau_{xy} & 0 & \sigma_y & 0 \\ 0 & 0 & 0 & 0 & \sigma_z \end{bmatrix}, \tag{26}$$

where stresses σ_x, σ_y, σ_z, τ_{xy} are determined from the static problem:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \end{Bmatrix} = [D][B]\{\delta\}. \qquad (27)$$

Results of analysis of paper stability in the elements of packages using the axi-symmetric model

A thin rectangular structure parallel to the axial coordinate is analyzed. For the static problem the following boundary conditions are assumed: on the lower boundary u=v=0, on the upper boundary u=0 and v=-1. For the eigenproblem on the lower and the upper boundaries all the displacements are assumed equal to zero.

The first eigenmode of stability is presented in Fig. 26, the second eigenmode of stability is presented in Fig. 27, …, the eighth eigenmode of stability is presented in Fig. 33.

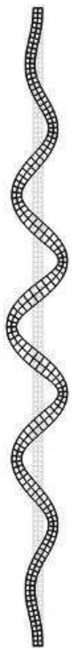

Fig. 26. The first stability eigenmode

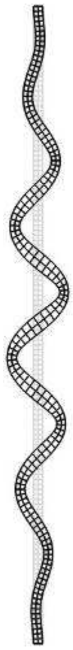

Fig. 27. The second stability eigenmode

Fig. 28. The third stability eigenmode

Fig. 29. The fourth stability eigenmode

Fig. 30. The fifth stability eigenmode

Fig. 31. The sixth stability eigenmode

Fig. 32. The seventh stability eigenmode

Fig. 33. The eighth stability eigenmode

Conclusions

The one-dimensional model for the analysis of paper stability in the printing machine is based on the assumption that a paper is analyzed as a beam with additional stiffness due to its static longitudinal compression.

The static problem of longitudinal motion of a bar is solved, assuming that the displacements at the ends of the analyzed paper are given. Then the stability of the investigated paper as of a beam having additional stiffness due to the static compression determined previously is analyzed.

The setup for experimental investigations was designed and created which enabled to determine the images of the stability eigenmodes of the polymeric film HDPE for uniaxial unidirectional compression of the film by using the method of digital speckle photography.

The configurations of the images of stability eigenmodes of the polymeric film HDPE obtained by using the method of digital speckle photography characterize the quality of stress uniformity of the polymeric film in the flexographic printing machine and the uniformity of loading of the polymeric tape.

The two-dimensional model for the analysis of stability of a paper in the printing machine is based on the assumption that a paper is analyzed as a plate with additional stiffness due to its static compression in the plane of the paper.

The static problem of the plane stress is solved, assuming that the displacements at the edges of the analyzed paper are given. Then the stability of the investigated paper as of a plate having additional stiffness due to the static compression determined previously is analyzed.

The axi-symmetric problem for the analysis of stability of a paper is based on the assumption that a paper has additional stiffness due to its static compression.

The static problem is solved, assuming that the displacements at the edges of the analyzed paper are given. Then the stability of the investigated structure because of the additional stiffness due to the static compression determined previously is analyzed.

The obtained results are used in the process of design of the elements of the printing machine.

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