DETERMINATION OF YARN WAVINESS PARAMETERS FOR C/C WOVEN COMPOSITES

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Introduction

The woven composite reinforcements are created by orthogonal yarn interlacing, which produces yarn undulation (waviness). Yarn waviness strongly influences namely elastic properties of woven composites. Therefore properties prediction is based upon detailed geometric description of the reinforcement. Yarn undulation is usually quantified by means of inclination angle distribution. Inclination angles can be derived from mathematical description of actual yarn shape using polynomial function [1], spline [2] or wavelets for instance. However, regularly repeated yarn interlacing in woven structures offers a more general description taking into account the periodicity of waveforms and consequently makes possible the application of Fourier series. Application of Discrete Fourier transform (DFT) enables not only the determination of inclination angle distribution, but also the finding of wavelength, amplitude and phase angle (connected with yarn nesting) of crimp waves. Periodicity parameters define the unit cell dimensions needed for properties prediction based on utilization of unit cell models.

Theoretical Background

The actual quasi-periodic yarn shape y(x) can be considered as a superposition of a definite number of harmonic courses with amplitudes Ai, phase angles Φi and wavelength L.

$$y(x) = A_0 + A_1 \sin\left(\frac{2\pi x}{L} + \phi_1\right) + .. + A_n \sin\left(\frac{2\pi x}{L} + \phi_n\right) \quad (1)$$

The accuracy of yarn shape approximation depends on the number of selected harmonics. Statistical reliability of periodicity parameter determination increases with increasing number of successive crimp waves, which are approximated. For this reason computer-aided assemblage of resulting image from its partial parts had to be solved before image processing and extraction of yarn centerline coordinates.

Experimental

Investigated material

The composites were reinforced with plain weave (PW) or 5HS satin weave fabric made of Torayca T800 (6K) fibers. Eight layers of the fabric were soaked with phenol-formaldehyde resin (carbon matrix precursor), cured during molding to three compression levels (about 0.3, 0.5 and 1 MPa) and carbonized in nitrogen.

Digital image processing

The composite structure was studied in two mutually perpendicular cross-sections in warp and weft direction. Polished specimen surfaces were scanned at magnification 73x using macroscope and converted to a binary image by the use of RGB video camera connected with image analysis system LUCIA G, LIM Ltd. Czech Republic. Home-made software, written in language DELPHI enables automatically the assemblage of resulting image using a convolution of overlapping parts, furthermore identification of yarn boundaries semi-automatically, determination of yarn centerline coordinates with optional step (0.05 mm in our case) and data processing by the use of DFT, details in [3].

Data processing

Discrete Fourier transform was applied to yarn centerline coordinates. The program allows to select the dominant harmonics, or selects the given number of the highest harmonics automatically, calculates the approximate yarn axis by the use of formula (1) and compares it with an experimental shape. Typical spectrum obtained by DFT is shown in Fig.1. Periodicity parameters of yarn waviness can be determined from significant maximum harmonics. Besides wavelength and amplitude, phase angle and phase shift can be obtained for each layer of woven reinforcement [4]. Detailed analysis of yarn waviness by means of DFT is prepared for publication. The inclination angle is determined in accordance with definition as the first derivative of analytical form (1), describing yarn waviness.

Results and Discussion

Results are summarized in Fig.3-5 and Table 1. Each specimen provided six sets of measurement: three for various compression levels for both warp and weft yarns. Each set involved 12 samples with sample area of 64 mm^2 (total area of 760 mm^2) for the highest compression level. For the lowest compression level sample area differed in dependence of weave-pattern of specimens.

Sample area of 83 mm^2 (1000 mm^2 in total) was for PW composites and 104 mm^2 (1248 mm^2 in total) was for 5HS composites in consequence of float length of yarns. Figures 3 and 4 show DFT approximation of actual yarn shape for PW and 5HS composite, respectively. In general we can see two tendencies in the changes due to the increasing compression level:

- straightening of yarn segments and
- distortion of yarn waveforms, caused by locking of fabric layers into each other. For PW composite straightening of yarn segments is relatively small and distortions, rising with increasing compression level, are the dominant tendency (Fig.3). This trend is also confirmed with inclination angle distributions, where we can see relative high occurrence of angles, which differs from zero (Fig.5). On the contrary of PW, straightening of yarn segments is the dominant tendency for 5HS composites (Fig.4). Inclination angle distributions exhibit very high occurrence of angles about zero, namely for the highest compression level (Fig.5). We can note that the application of the highest compression level produces the small waviness of yarn runs as the result of locking of fabric layers into each other (Fig.4). Results in Tab.1 document the relative formability of satin structure, caused by the long runs (floats) of yarn and relative rigidity of plain-weave structure, given by close yarn spacing. Wavelength of waveforms exhibits a small sensitivity to composite pressing degree; it is fixed by tow pitch. Decline of waveform amplitude with the increasing pressing degree is significant for satin (by 53%) and it is negligible for PW structure (by 4%). Coefficients of variance (relative errors) are in general higher for satin in comparison with PW structure and for weft (fill) yarns in comparison with warp yarn. It notices the higher variability of yarn shape in loosely interlaced structures of yarn and fabrics.

Conclusion

New approach for description of yarn waviness periodicity was developed. It is based on utilization of DFT for approximation of actual yarn paths in composite structure. Approximation of 10 successive crimp waves at least is necessary for the achievement of good statistical reliability of results. The main parameter of woven structure periodicity-wavelength of crimp waves-does not change during manufacture of both PW and 5HS composites. Values of inclination angle rise with increasing compression level namely in PW composites. This change of the structure produces the relevant change in elastic moduli of composites as it was shown in [5] see Fig.2.

References

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pressing degree [MPa]	plain-weave					satin				
	wavelength [mm]		amplitude [μm]		sample size	wavelength [mm]		amplitude [μm]		sample size
	warp	weft	warp	weft		warp	weft	warp	weft	
~ 0.3	3.3	3.4	60	72	780	7.8	7.6	78	84	400
~ 0.5	3.3	3.4	57	64	780	7.8	7.5	72	62	400
~ 1	3.3	3.4	56	60	1050	7.8	7.4	36	40	520
CV [%]	3	7	13	15	-	12	21	19	20	-

Tab.1 Influence of composite pressing degree on yarn waviness parameters. Sample size (number of crimp waves) is the same for both warp and weft yarn. Number of the successive crimp waves, which are taken into one DFT spectrum is 11 for PW and 6 for 5HS.

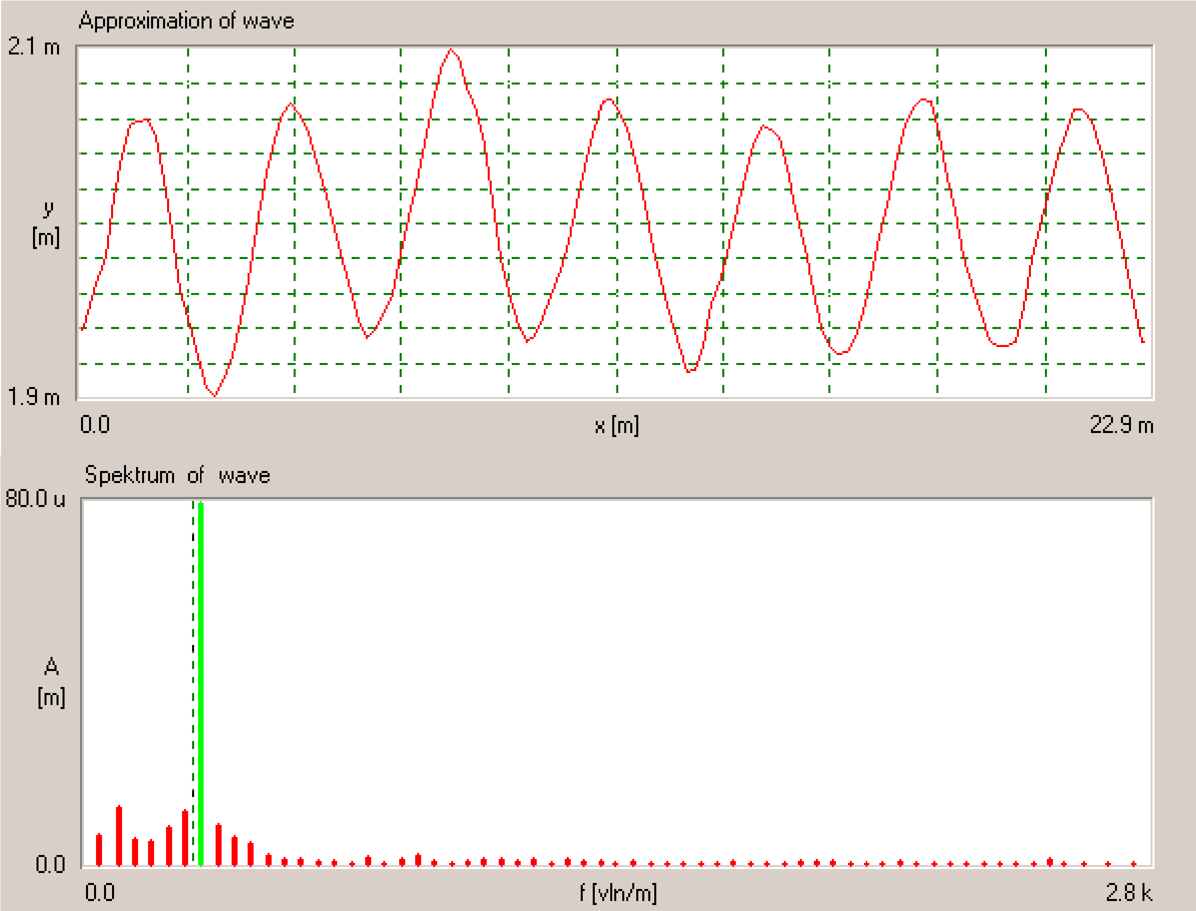

Fig.1 Yarn centerline approximation and DFT spectrum

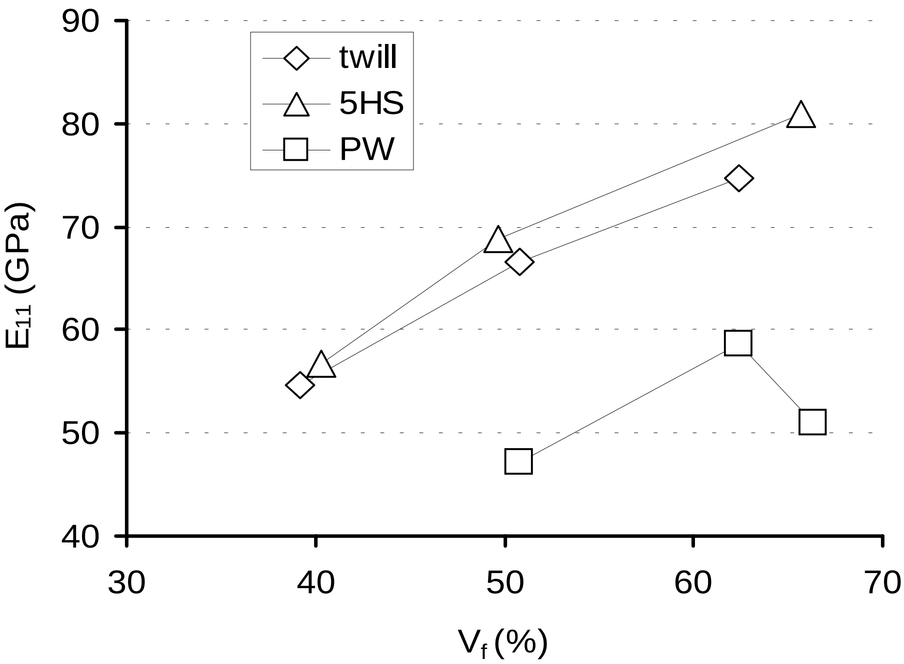

Fig.2 Tensile dynamic modulus of twill, 5HS, and plain weave reinforced composites *vs.* volume fraction of fibers

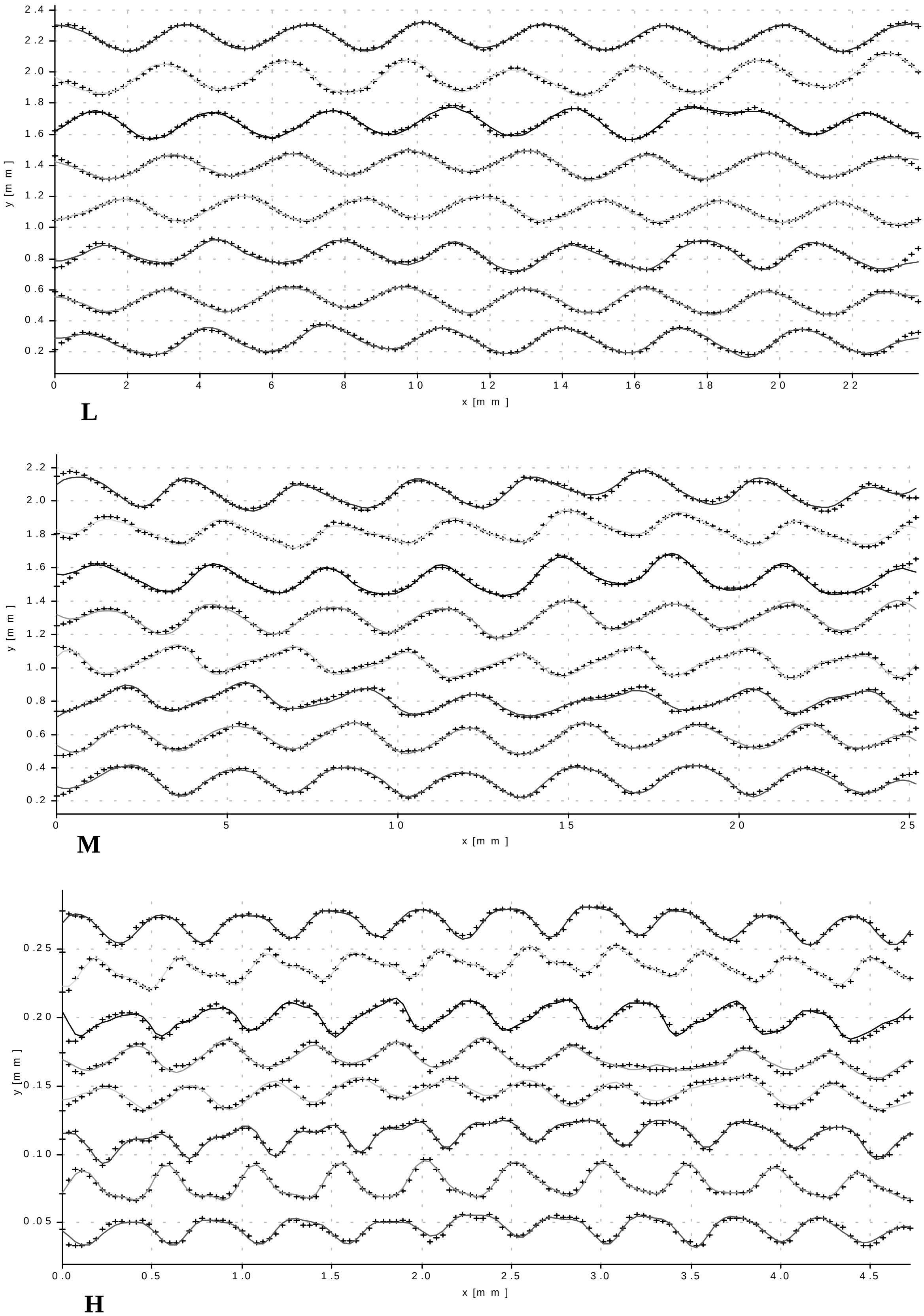

Fig.3 DFT approximation of actual yarn shape for PW composites – effect of pressing degree (L ~ 0.3 MPa, M ~ 0.5 MPa and H ~ 1 MPa)

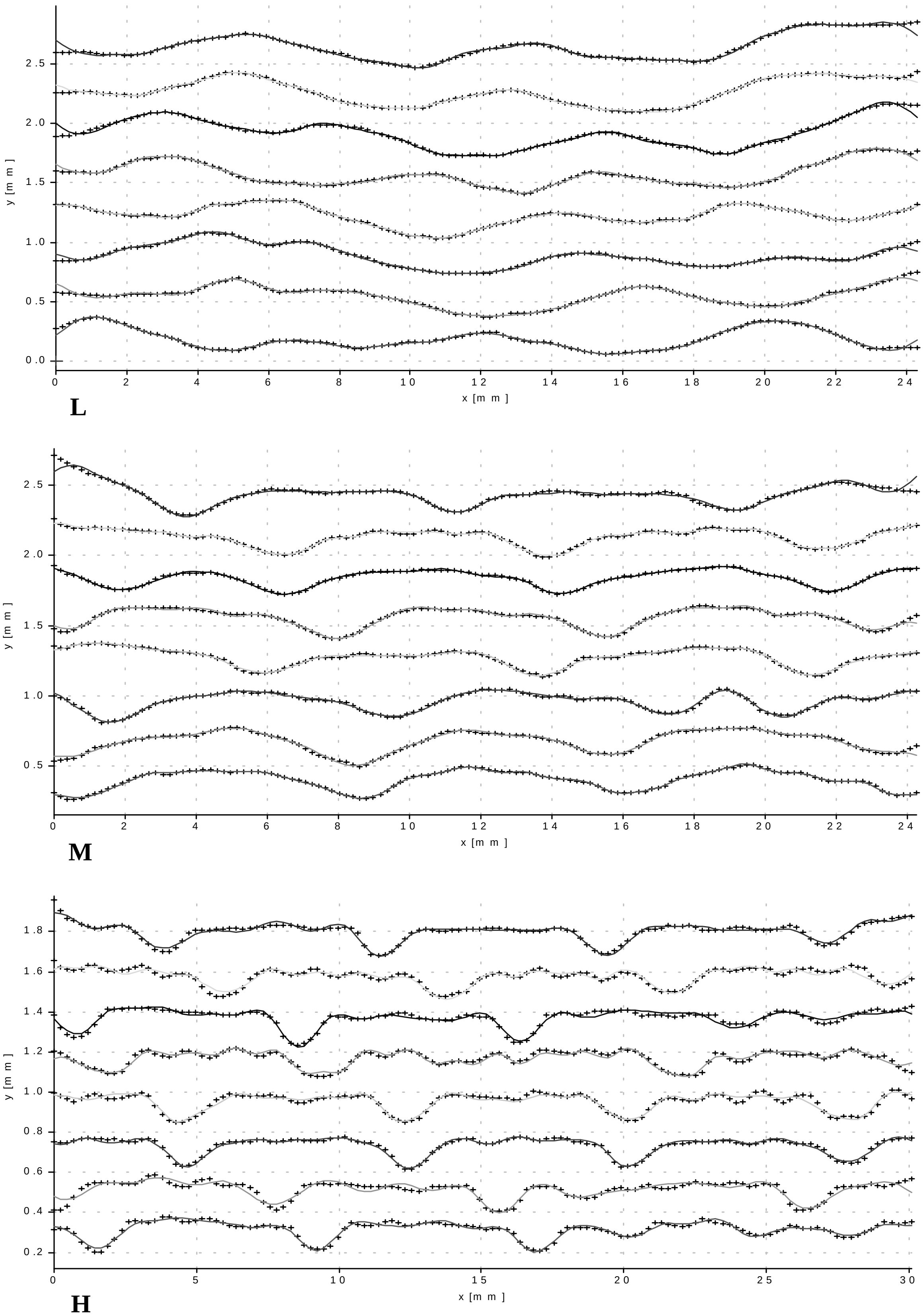

Fig.4 DFT approximation of actual yarn shape for 5HS satin composites – effect of pressing degree (L ~ 0.3 MPa, M ~ 0.5 MPa and H ~ 1 MPa)

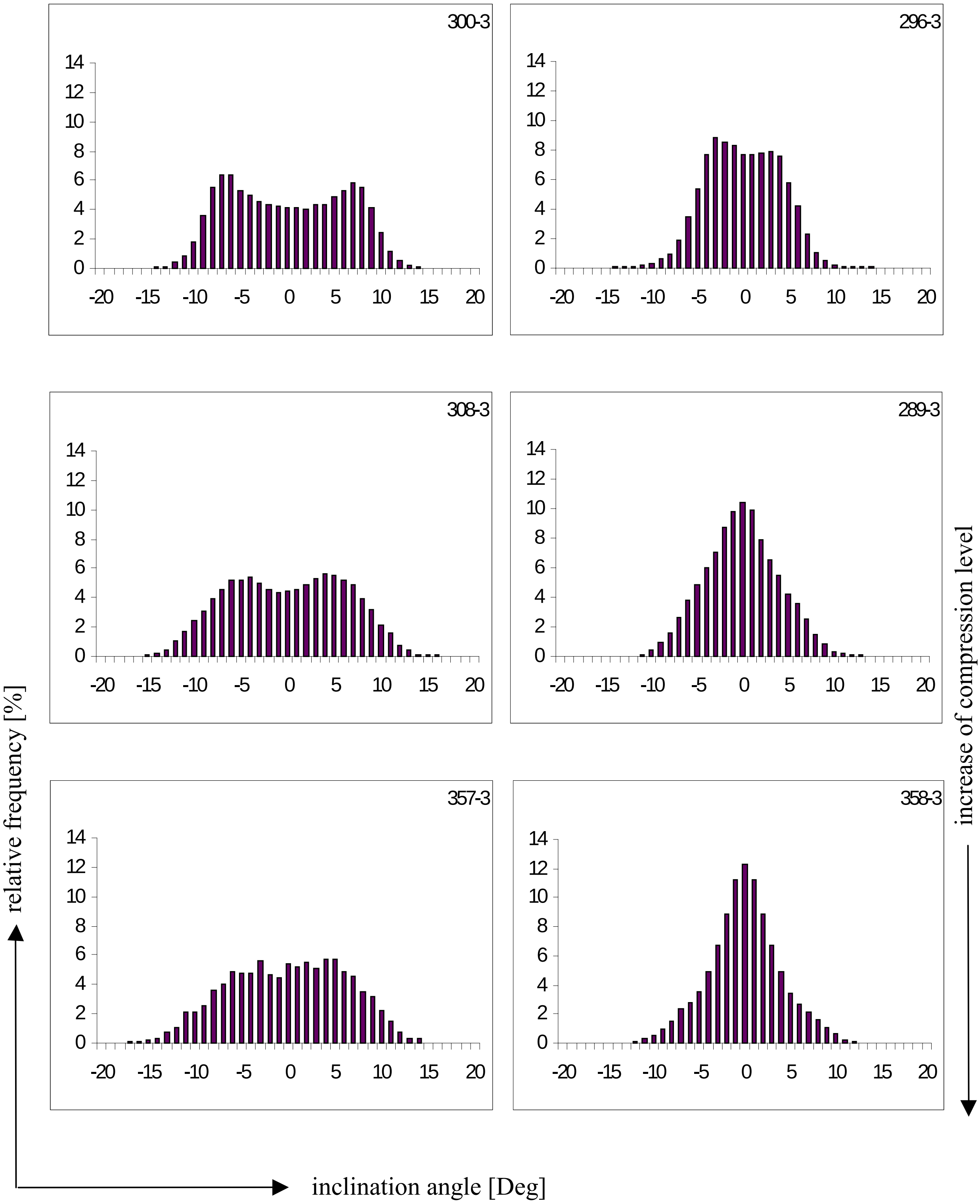

Fig.5 Changes in inclination angle distribution for warp yarns due to increasing composite compression level, sample size (number of angle measurement) for each histogram is 67 200