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Constitutive Model of Unplasticized Polyvinyl Chloride for Numerical Stress-Strain Analysis

Veselin Iliev[1]*, Radan Ivanov[2], Zlatka Geshkova[1], Vasil Samichkov[1], Nikolai Yavorov[1]

[1]*University of Chemical Technology and Metallurgy, Sofia, Bulgaria*
[2]*National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Sofia, Bulgaria*

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ABSTRACT

The mechanical properties of unplasticized polyvinyl chloride (UPVC) are modified during the manufacturing process of a product. Therefore, the data on the mechanical behavior of this material available in the scientific literature varies greatly. This requires that the type of mechanical behavior of the material and the corresponding constitutive model to be determined on a case-by-case basis. In the present work, an investigation of the mechanical behavior of UPVC is presented in order to select a model, best describing the material behavior at highly heterogeneous stress distributions within the structure.

Twelve specimens from different parts of PVC window frames and sashes made by Weiss Profil, Bulgaria, have been tested under tension according to Bulgarian standard 12602-81. The mechanical behavior of the material and the corresponding material characteristics have been determined from the stress-strain curve obtained by the test. The research is directed at identifying the material model parameters, incorporated in FEM software used for the stress-strain analysis of load-bearing structures.

Keywords: UPVC stress tests, material constitutive models, mechanical behavior of materials.

INTRODUCTION

Unlike plasticized PVC, unplasticized polyvinyl chloride has high stiffness, high strength and improved environmental resistance. This makes it particularly suitable for window frames. One of the most important material characteristics for such an application is the set of mechanical properties. Usually, the modulus of elasticity and the material strength are sufficient for basic design calculations and sizing of individual frame elements. The values of these properties can be found in many references. Most often these are generalized data submitted by manufacturing companies. Some values found by the authors are given in Table 1.

However, it is sometimes necessary to carry out a detailed study of the mechanical behavior of frames and sashes of windows under static and cyclic loads, caused by service or transport

**Correspondence to: Veselin Iliev, University of Chemical Technology and Metallurgy, 8 Kliment Ohridski, 1756 Sofia, Bulgaria, E-mail: veso@uctm.edu*

Table 1. Mechanical properties of UPVC.

Origin	Density [kg/m^3]	Tensile Strength [MPa]	Module of Elasticity [GPa]
Creative Mechanisms [1]	1.35 - 1.45	34 - 62	-
AWWA Manual M23 [2]	-	34.5	1.93
3DINSIDER [3]	1.35 - 1.45	40 - 62	3.38
MakeItFrom [4]	1.4	47	3.70
GoodFellow Group [5]	1.4	25 - 70	2.5 - 4

conditions and storage. In such cases, the tensile strength and the modulus of elasticity, suggesting linear elastic behavior of the material, are not sufficient. More complex constitutive equations are needed to describe the real mechanical behaviour. Results from a more detailed study on the mechanical behavior of unplasticized polyvinyl chloride can be found in [6 - 8]. From the curves giving the relationship between stress and deformation, presented in these references, it can be concluded that a relatively good description of the mechanical behavior of these materials can be made using a bilinear hardening model. Another conclusion that can also be made is that the mechanical properties are significantly influenced by the modification of the polymer material according to its specific application in engineering. This requires an ad-hoc laboratory test of the material in the absence of detailed information about its mechanical behavior from the manufacturer. This paper presents the results of tensile tests and the derivation of the constitutive equation for a material used for PVC frame production by Bulgarian manufacturers. The equation can be used in the numerical procedures for calculating the stress-strain state of the elements, made by this material.

EXPERIMENTAL

The tests were performed with a test machine Zwick/Roel Z010 with a deformation rate of 100mm/s. Twelve specimens from different parts of PVC window frames and sashes made by Weiss Profil Bulgaria were tested under tension according to standard BDS 12602-81, [9]. The specimens were divided into four series and Fig.1 shows the locations on the UPVC frame from which the specimens of each series were cut.

The specimens had the same shape and working length as required by the standard (Fig. 2). Because the specimens were cut from different places, they had different cross-section sizes (Table 2). When the specimens were fixed in the test machine heads, some pre-test deformation was observed. To eliminate the impact of this effect on the final results, as well as the influence of the nonlinear behavior of the material

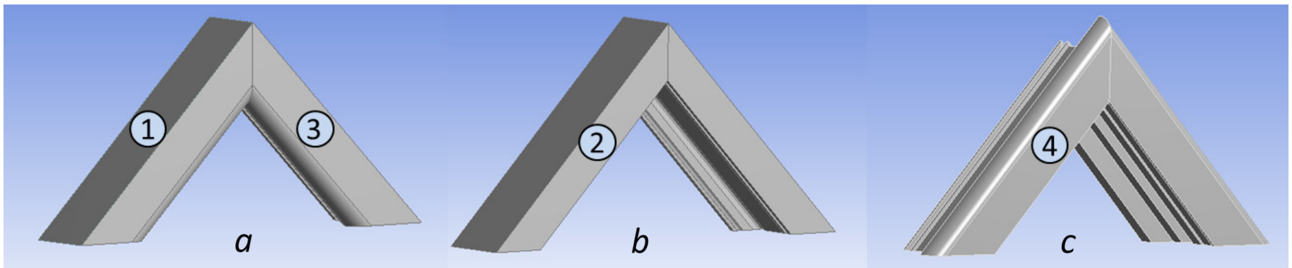

Fig. 1. Specimen cutting locations for each series: a – outer part of the sash, b - inner part of the sash, c - inner part of the frame.

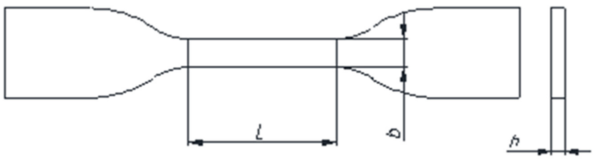

Fig. 2. Shape and size of specimens: L - length of narrow section; b - width; h – thickness.

near yield stress point, two stress values were chosen - σ_{low} and σ_{high}. The stress-strain curve between these values was used to establish the linear elastic properties of the material. The experimental results were processed using the ASTM D638 standard methodology available in the test machine software, which is closest to the methodology used by us.

Table 2. Cross-section size.

	Series 1	Series 2	Series 3	Series 4
b, mm	6,4	6,4	6,4	6,4
L, mm	25	25	25	25
h,mm	2,3	2,3	2,2	2,4

Table 3. Test results.

Series	No.	$L_{0\,CH}$ mm	L_0 mm	σ_{low} MPa	σ_{high} MPa	E_t MPa	E_{Sec} MPa	σ_{x1} MPa	σ_Y MPa	ε_Y %
1	1	60.00	60.00	9.952	36.995	2700	2750	46.5	59.6	4.3
	2	60.00	60.00	17.087	40.297	2900	3030	45.4	60.4	3.4
	3	60.00	60.00	11.653	36.175	3070	3110	44.1	62.4	3.7
2	4	60.00	60.00	9.292	38.931	2960	3060	44.9	61.1	3.6
	5	60.00	60.00	4.679	29.512	2760	2750	44.5	60.3	3.8
	6	60.00	60.00	6.354	35.790	2940	2980	43.3	60.0	3.7
3	7	60.00	60.00	9.856	39.370	2810	2960	44.1	58.0	3.8
	8	60.00	60.00	10.530	40.006	2810	2970	44.7	58.6	3.8
	9	60.00	60.00	7.312	35.901	2720	2790	41.8	56.4	3.9
4	10	60.00	60.00	8.935	18.859	2480	2520	40.5	55.5	4.0
	11	60.00	60.00	9.862	18.890	2260	2290	41.6	55.3	4.0
	12	60.00	60.00	10.198	39.739	2950	3000	46.4	63.2	3.8

Table 4. Cross-section area.

Series	No	A_0 [mm^2]	A [mm^2]
1	1	14.72	8.64
	2	14.72	8.5
	3	14.72	7.36
2	4	14.72	7.04
	5	14.72	7.2
	6	14.72	7.99
3	7	14.08	7.68
	8	14.08	7.36
	9	14.08	6.75
4	10	15.36	8.16
	11	15.36	8.64
	12	15.36	9.12
Average		14.72	7.87

RESULTS AND DISCUSSION

The numerical results for the basic mechanical properties, obtained by the experiment, are presented in Table 3. For basic mechanical calculation, the important values are yield stress ε_y, module of elasticity E and tangential moduli of elasticity E_t. The close values of the two modules between fixed σ_{low} and σ_{high} indicate the linear-elastic behaviour of the material in this region. Usually, the yield stress is used for determination of the allowable stress value, since beyond the yield stress the deformation increases rapidly, i.e. the material load resisting capacity decreases significantly.

More complete information about material behavior beyond yield stress can be obtained from the stress-strain diagrams (Fig. 3). We assume that the deformation curves are close enough to allow averaging the values obtained for all twelve samples.

The large length of the strain softening section of the diagrams indicates a significant decrease in the initial cross-section area A_0 of the specimen up to the fracture. This requires that the true stress diagram (σ = force/actual area, ε) be constructed for the purposes of the material properties analysis. The ultimate cross-section area A is obtained from the size of the fractured specimens. The actual area for computing the true stresses at the intermediate points of the diagram is obtained assuming uniform reduction during the test. The values of the initial and the ultimate cross-section area for the specimens used are given in Table 4. The engineering stress and true stress diagrams obtained by averaged values of the stresses are presented in Fig. 4. In the true stress diagram, the softening section (with negative modulus) from the engineering stress diagram becomes a

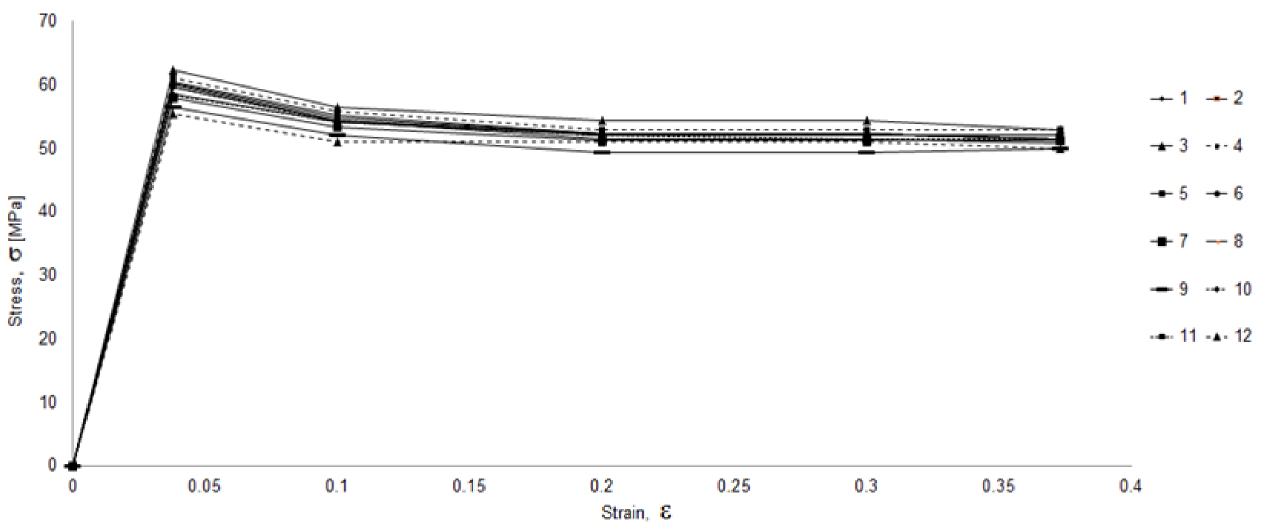

Fig. 3. Stress-strain diagrams obtained by the tensile test.

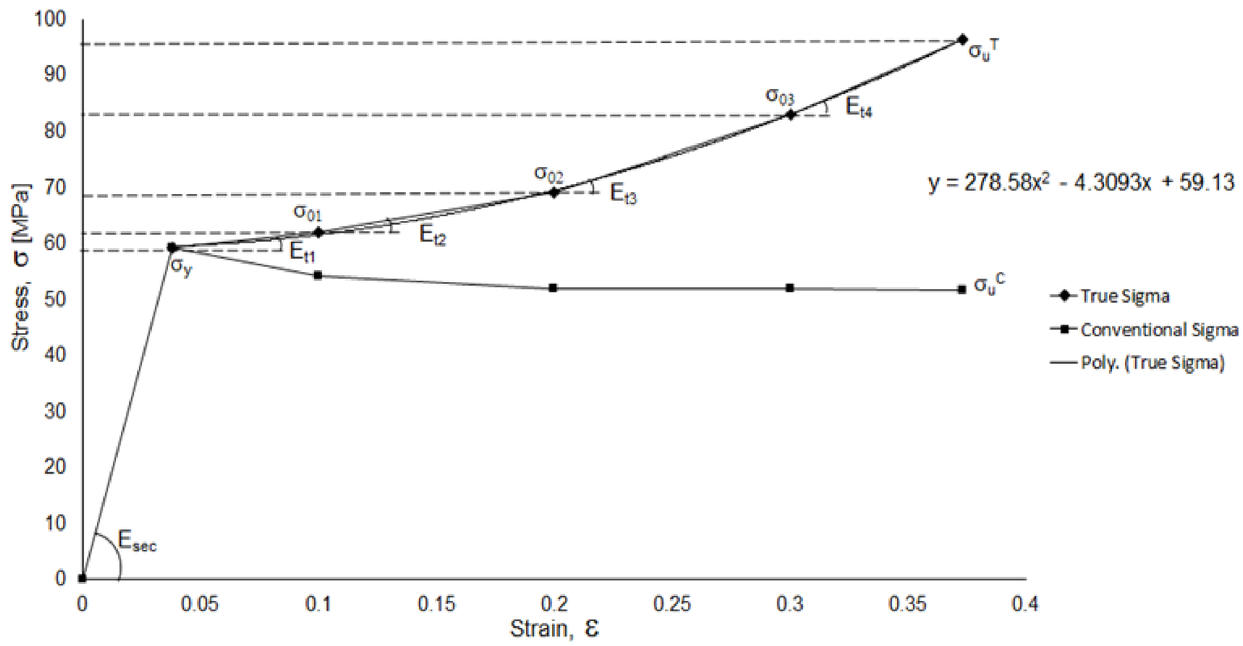

Fig. 4. Averaged stress diagrams.

hardening section (with positive modulus).This section has an untypical concave shape, but it can be successfully described by a multilinear hardening model. Here, the multilinear hardening model is considered in accordance with the Ansys theoretical guide, [9], and isotropic hardening is described by a multilinear effective stress versus effective strain curve. It is assumed that the effective stress and the effective plastic strain follow the same stress-strain curve as in the uniaxial case [10]. The initial slope of the curve is the elastic modulus E_{sec} of the material. Beyond the initial yield stress σ_y, plastic strain develops and diagram stress vs. total strain continues along a line, with slope defined by the tangent modulus.

Table 5. Material characteristics.

Modulus [MPa]		limit of validity [MPa]	
E_{sec}	2860	σ_y	60
E_{t1}	22	σ_{01}	62
E_{t2}	56	σ_{02}	70
E_{t3}	111	σ_{03}	83
E_{t4}	167	σ_U^T	96

The multilinear hardening behavior is described by a piecewise linear stress - total strain diagram, starting at the origin and defined by sets of positive stress and strain values.

For the tested material the curve (Fig. 4) can be described by eq.1, and the tangent modulus can be obtained from its first derivative (eq. 2).

$$\sigma = 278.58\,\varepsilon^2 - 4.3093\,\varepsilon + 59.13 \quad (1)$$

$$E_t = 557.16\,\varepsilon - 4.3093 \quad (2)$$

The material characteristics of the tested material are given in Table 5.

CONCLUSIONS

More complex than linear constitutive equations are needed to describe the real mechanical properties in case of a detailed study of window frames and sashes, made by UPVC. For describing the mechanical behavior of this material, a multilinear isotropic hardening model given by effective-stress versus effective-strain curve can be used. For UPVC it can be assumed that the stress-strain curve for effective stress is the same as for the uniaxial case. Uniaxial test results show the existence of a large softening zone in the engineering stress-strain diagram and a hardening zone in the true stress diagram. To obtain the characteristics of the isotropic hardening model, a piecewise linear stress - total strain diagram should be created.

Acknowledgements

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