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ARAŞTIRMA MAKALESİ/**RESEARCH ARTICLE**

NUMERICAL MODELLING OF A SHORT TENSILE COUPON FOR GLASS FIBRE REINFORCED PLASTICS

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ABSTRACT

Fibre reinforced plastic structural members are currently produced successfully by pultrusion and are used in a number of civil engineering applications. The measurement of the mechanical properties of highly orthotropic material is necessary for numerical structural analysis and design. The mechanical properties of composite materials are determined by specific coupon test methods or by analytical models. However, pultruded or moulded fibre reinforced plastic structural sections and components may not possess the dimensions to permit the extraction of standard length coupons, as defined by the most commonly used standards, for the determination of material properties. The shape of the short tensile coupon is (<60mm long) established to circumvent this limitation using a finite element representation to determine the elastic properties of the fibre reinforced plastic materials.

Key Words: Glass fibre reinforced plastic, Orthotropic material, Mechanical properties, Numerical analysis, Tensile coupon.

CAM ELYAF TAKVİYELİ PLASTİKLER İÇİN KISA ÇEKME KUPONLARIN NUMERİK MODELLENMESİ

ÖZ

Cam elyafı takviyeli plastik yapı elemanları ön gerilmeli olarak üretilmekte ve birçok inşaat mühendisliği alanında kullanılmaktadır. Nümerik analiz ve tasarımların yapılabilmesi için ortotropik malzemelerin mekanik özelliklerinin bilinmesi gerekir. Kompozit malzemelerin mekanik özellikleri özel test metodu ile ya da analitik olarak bulunabilir. Ancak çekilmiş ya da kalıplanmış cam elyaf takviyeli yapı profilleri çekme deneyi için gerekli standart numune boyunu vermeyebilir. İstenilen boydaki (<60mm uzunluk) kısa çekme kuponlarının modelleri bu kısıtlamayı ortadan kaldırabilmek için sonlu elemanlar metodu yardımı ile belirlendi.

Anahtar Kelimeler: Cam elyaf takviyeli plastik, Ortotropik malzeme, Mekanik özellikler, Nümerik analiz, Çekme kuponu.

1. INTRODUCTION

Within the past four decades there has been a rapid increase in the development of advanced composites incorporating fine fibres, termed fibre reinforced plastic (FRP). The majority of composites used in the construction industry are based on polymeric matrix materials. Factors in choosing polymeric composite materials for structural engineering applications are: lightweight, non-corrosive, chemically resistant, possess good fatigue strength, non-magnetic, and, subject to the materials selected, provide electrical and flame resistance. Material surfaces are also durable and require little maintenance (Anon, 1989).

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The pultrusion process is a proven manufacturing method for obtaining lengths of high quality fibre reinforced plastic components having consistently repeatable mechanical properties (Werner, 1984). In this method, a continuous E-glass fibre reinforcement in the form of alternate layers of randomly oriented mat and layers of unidirectional roving bundles are pulled through a resin impregnator and then on through a heated die to form continuous prismatic members similar in geometry to those produced by the steel industry (Mallick, 1997).

Assuming a state of plane stress, measurement of the mechanical properties of the composite material is necessary for numerical structural analysis and design. A fundamental assumption used when determining the elastic properties of the material from a tensile test is the existence of a uniform state of strain within the gauge length. The gripping action of the jaws, in applying the axial load, restrains the coupon displacement in the transverse direction such that the corresponding strain, ε_y, is similarly restrained. The effects cause the strain distribution at mid-length (in the vicinity of the gauge) to become non-uniform for a short coupon. Consequently, $\varepsilon_x = P/E_x A$ is not valid as the state of strain at the centre of the coupon and is not consistent with the assumed value of stress, $\sigma_x = P/A$.

Classically, the undesirable constraining effects of the jaws have been minimised by providing an adequate coupon length. Therefore, the effects of zero transverse strain at the boundary of the gripping are dissipated leading to a strain distribution complying with the assumptions in (1). However, the geometries of many structural FRP sections prevent the extraction of a standard length specimen (typically in excess of 250mm) for the evaluation of elastic properties in the transverse direction. Despite of using non-standard tests and outcomes (Abd-El-Naby, 1992; Davalos et al., 1996; Sonti and Barbero, 1996), the provision of the specification of a short coupon satisfies requirement to ensure the determination of reliable material properties.

Finite element method has been used effectively to establish test specimen characteristics and loading configurations for composite materials. Reported research has concentrated on the improvement of standard length coupons in aiming to reduce stress concentrations at the clamping mechanism leading to an underestimate of tensile strength of the test material. The off-axis techniques for the tension specimens are good example of the application of numerical methods (Cron et al., 1988). The influences of tabs on the indicated strength of FRP specimens and the level of clamping were investigated using a linear-finite-element method. The results indicated that it is possible to produce nearly uniform states of stress in the gauge length with the proposed tab and clamping configurations. Sandhu and Sendeckyj (Sandhu and Sendeckyj, 1985) determined that a state of uniform axial stress within the test section could be achieved if the grips were allowed to rotate and the fibre angle of the parent tab material and tab geometries were simultaneously optimised. Kural and Flaggs (1983) used the results of two-dimensional plane stress finite element analyses to improve the design by achieving increased uniformity of the strain and minimisation of the stress concentrations within a tensile coupon near the tabs. Foos et al. (1992) used two-dimensional linear finite element analyses for the design of the end tabs to improve the uniformity of the strain state in a tensile test specimen in order to obtain an accurate measurement of the tensile strength of graphite/epoxy composites. It was demonstrated that the uniformity of the strain states within the tensile test specimens could be improved by changing (modifying) the coupon design using the results of finite element analysis. Linear elastic analysis was also found to be adequate in this case.

The purpose of this study present study is to propose the shape of a short tensile coupon for the determination of both elasticity modulus and strength of FRP. Numerical models are used to predict strain fields at the centre of coupons of different shapes under length constraints for comparison with ASTM D3039 (1996). The development of a short coupon specification giving the lowest divergent strain field across the centre of the coupon is presented.

2. COUPON GEOMETRIES-FINITE ELEMENT ANALYSIS

Numerical models of proposed test coupon geometries have been prepared and analysed using the finite element system, LUSAS. A typical numerical model of a coupon consists of two types of isoparametric elements. The first is a tetrahedral solid continuum in three dimensions (*PN15*), defined by fifteen nodes (six on the top and bottom surfaces and three mid-side). Three translational degrees-of-freedom (d.o.f) (u, v, w) are specified at each node. The second type is a hexahedral solid continuum element in three dimensions (*HX20*) with twenty nodes (eight on the top and bottom surfaces and four mid-side) and the same three translational d.o.f at each node. Both element types feature quadratic shape functions and are capable of modelling non-rectangular shapes and curved boundaries in the plane, consistent with potential coupon geometries. Combinations of tetrahedra and hexahedra have been used to ensure a smooth mesh transition along the length of the element as determined by the element geometry.

The main configurations of the short coupon and ASTM D3039 coupon models are shown in Figure 1 and Figure 2. An applied uniform shear stress (surfaces S1 – S4) has been used to represent the application of the axial load to the coupon (surfaces S1-S4, Fig. 1). The physical support conditions have been introduced through the following displacement constraint equations:

$u \neq 0,\ v=0,\ w \neq 0,$ (surfaces S1-S4) (1)

$u=0,\ v \neq 0,\ w \neq 0,$ (surface S5) (2)

Constraint (1) admits longitudinal displacement but prevents the Poisson's ratio effect in the y-direction, consistent with the gripping effect of the jaws. (In a conventional plane stress problem it would be normal to restrain only the *u* (and *w*) displacement, thus permitting the Poisson's ratio effect in the *y*-direction). (2) effectively prevents the numerical representation from being poorly conditioned as a result of a potential rigid-body translation in the global *x* direction and rigid body rotation about the global *z*-axis.

3. ASTM D3039 MODEL

To establish the validity of the numerical formulation, a numerical model of a coupon described in ASTM D3039, has been studied with estimated orthrotopic material properties of the pultruded FRP box section, which were calculated using micro-mechanical models and classical lamination theory (Sarıbıyık , 2000).

Assuming linear elasticity and a prismatic section, the longitudinal strain in the central region of the specimen, ε_x, is equal to *P* divided by E_x times *A*.

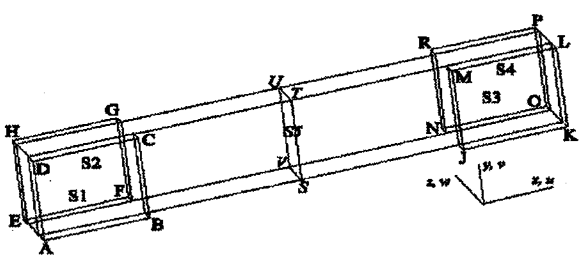

Figure 1. Schematic Coupon Model.

(S1→ABCD; S2→EFGH; S3→JKLM; S4→NOPR; S5→ STUV).

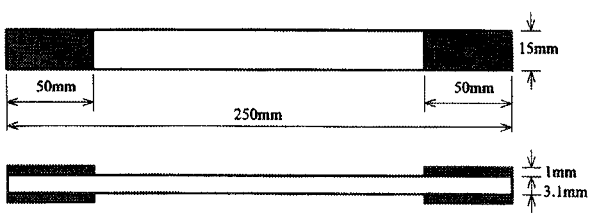

Figure 2. ASTM D3039 Test Coupon.

$$\varepsilon_x = \frac{P}{E_x A} \qquad (3)$$

where, *P* is applied load (15kN in this example), E_x is elasticity modulus in longitudinal direction (27.36kN/mm^2) and *A* is the cross-sectional area of the specimen (3.1mm × 15mm = 46.5mm^2).

The magnitudes of the analytical strain (ε_x=0.01179, (3)) and Gauss point results obtained from elements located at the centre of the "numerical coupon" coincide subjected to each other. The computed strain distribution is shown in Figure 3. for the entire coupon. The non-linearity (with length) of the axial strain beyond the extent of the tabs is clearly visible and is seen to dissipate rapidly towards to the centre of the coupon. Using this interval to display strain variations at the centre of the ASTM D3039 specimen would lead to no contours being displayed implying a strain variation of less than 0.6×10^{-4} in the gauge area. This is also confirmed by plotting the magnitude of the longitudinal strain across the width of the coupon as in Fig. 4. The equality of the analytical and computed strains at the centre demonstrates the validity of the numerical model, while the philosophy behind a minimum length is indicated by the strain smoothing away from the end restraints.

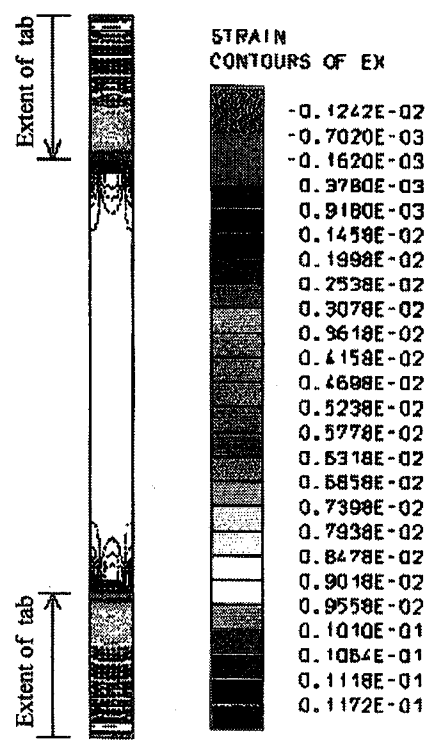

Figure 3. Strain Contours For ASTM D3039 Specimens In The Longitudinal Direction.

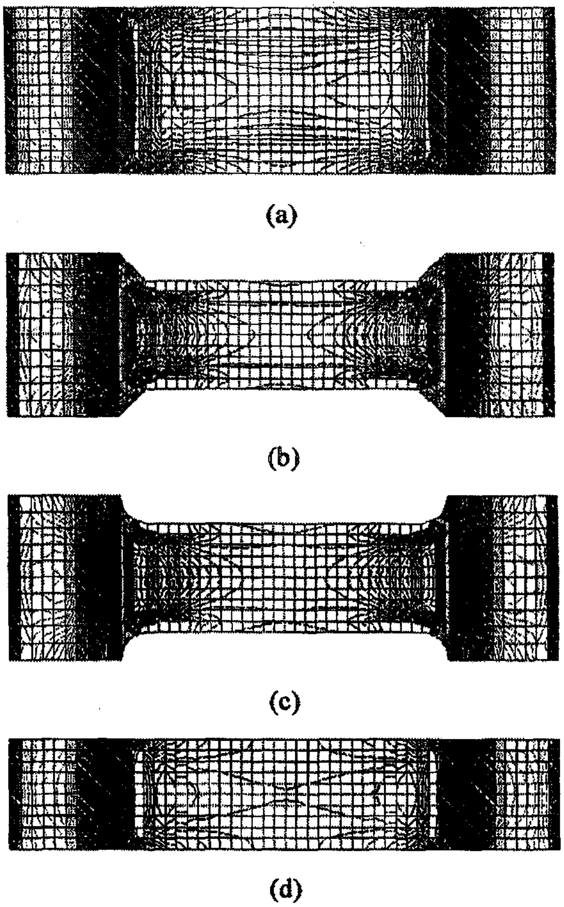

Figure 4. Contours Of Longitudinal Strain – 50mm Short Coupons.

((a) rectangular 15mm wide, (b) 45° linear transition, (c) 2.5mm radius transition, and (d) rectangular 10mm wide; longitudinal strain (ε_x) contour interval of 0.6x10^{-4}).

4. VARIATIONS OF "SHORT" COUPON MODEL (50mm)

4.1. Coupon Shape

Adopting the numerical modelling rationale described in the previous section, "short" coupons with a fixed length of 50mm, a thickness of 3.1mm and a gripping length of 10mm and two generic shapes have been analysed. A short version of the ASTM straight-sided coupon with 10mm and 15mm widths have been used to represent the first type. For the second type, the effects of strategies used to reduce the gauge width beside the gripping area on the central strain distribution has been investigated, especially in the context of promoting failure within the gauge area and away from the clamping zones. Two approaches have been used to develop the reduced width transition. The first is a simple 45° gradient (see Figure 4(b)) and the second an arc with a radius of 2.5mm and the origin chosen to generate a quarter circle (see Figure 4 (c)). Simple geometries have been proposed in order to assist in the fabrication of the coupons.

With a mesh of 1mm by 1mm squares plotted on the surfaces of the coupons (Figure 4), the quality of the strain distribution may be judged by the number of contours in the context of a typical strain rosette with plan dimensions 9mm wide by 6mm long (i.e. EA-13-060RZ-120). A comparison of longitudinal strain distributions at the centre of the numerical models (Figure 5) indicates that a coupon with a width transition introduced as an arc (denoted 50-2.5) performs well in comparison with the 15mm straight-sided geometry (denoted 50-15st). However, reducing the gauge width beyond the gripping area using an arc leads to high stress concentrations (0.5028/0.3226 = 1.56) with the strain needing to "flow" into the reduced section. This stress concentration (important in the determination of the material tensile strength) is higher in the case of the 45° linear transition example (denoted 50-45, see Fig. 4(b)) with a corresponding ratio of (0.6023/0.3226 = 1.87). The 10mm wide straight-sided performed well in comparison with a width transition introduced by a curve with a 2.5mm radius (Fig. 4(c)). The same strain contour interval of 0.6x10^{-4} is used for all diagrams, enabling a direct comparison of the uniformities of the strain field of each coupon type. A number of performance characteristics of the coupon geometries are inferred by the strain contour plots. For example, in comparing the 15mm and 10mm wide coupon results (Figure 4(a) and (d) respectively) it is clear that the strain field of one coupon can not be interpolated (about a line of symmetry). Furthermore, the rate of change of strain in the longitudinal direction is increased in the coupons involving a transition in width, with the effect exacerbated in the transverse direction at the same location, with negative implications in the accurate determination of the material length.

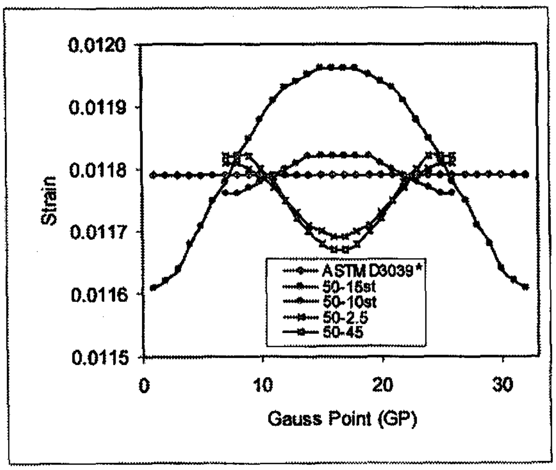

Figure 5. Influence Of Coupon Geometry On Longitudinal Strain Distributions.

(10mm gripping length; 50-15st = 15mm lectangular, 50-10st = 10mm rectangular, 50-2.5 = 2.5mm radius transition, 50-10-45= 45° linear transition). *Analytical strain coincident.

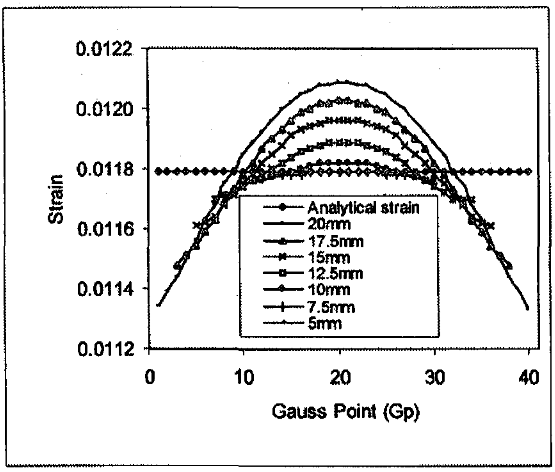

Figure 6. Influence Of Coupon Width On Longitudinal Strain Distribution.

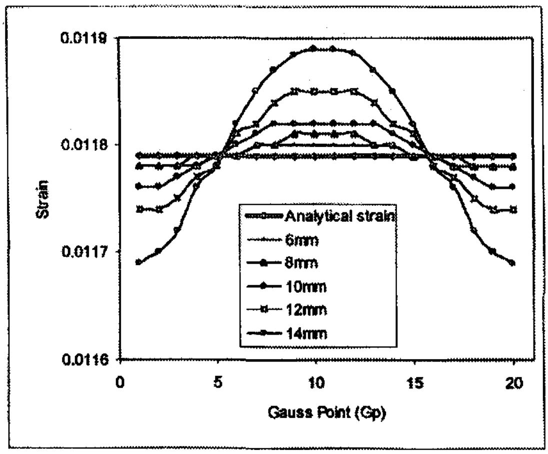

Figure 7. Influence Of Gripping Length On Longitudinal Strain Distribution.

4.2. Coupon Width

By changing the specimen width from 5mm to 20mm the effect of the coupon aspect ratio on the uniformity of the strain field has been investigated (Figure 6). It is clear that reducing gauge width also reduces the deviation of the computed strains across the specimen having a similar effect to increasing the length. It may also be noted that a specimen with a width of less than 10mm yields only a slight enhancement of the quality of the strain field. Furthermore, in considering physical testing limitations, a specimen width of less than 10mm does not provide sufficient gauge width to accommodate a three-element rectangular strain rosette. Therefore, the shape of the short coupon, selected by comparing strain variations across the centre of the gauge area and stress concentrations, is recommended to be straight sided with 10mm wide. It may also be noted that though only three potential geometry types have been assessed (reflecting fabrication constraints) the recommended straight-sided coupon geometry is consistent with ASTM guidance regarding highly uni-directional FRPs for strength determination. The significance of this work is in establishing an appropriate coupon width under a rectangular geometry constraint.

4.3. Gripping Length

The effect of the gripping length on the strain distributions at the centre of the short coupon subjected to gripping length variations is reported. Changing the gripping length from 6mm to 14mm has an effect on the quality of the strain field (Figure 7). As expected shorter gripping lengths tend to produce a more uniform strain distribution owing to the rapid dissipation of the clamping action of the jaws. Conversely, longer gripping length produced less uniform strain field as the gauge length decreased. Therefore, the uniformity of the strain field at the central region of the coupon is directly related to the gauge length. It can be seen from Figure 7, the influence of a gripping length of less than 12mm is not profound. Comparing the influences of geometry change (Figure 5) and gripping length (Figure 7) suggests that the effect of gripping length is less than the geometric variation. However the gripping length becomes significant in the determination of the material strength. For practical reasons it is not feasible to use a gripping length shorter than 8mm-10mm.

4.4. Coupon Length

Strain distributions at the centre of the short coupon subjected to length variations (Figure 8) show that for short lengths (less than 60mm) the computed strains in the central region of the coupon diverge from the analytical target. For specimens shorter than 60mm, the magnitude of possible error between the expected analytical and computed strains can be estimated. Fac-

Table 1. Evaluated Strain Correction Factors.

Specimen length (mm)	Correction Factor
≥60	1
55	1.001
50	1.003
45	1.006
40	1.012
35	1.021
30	1.048

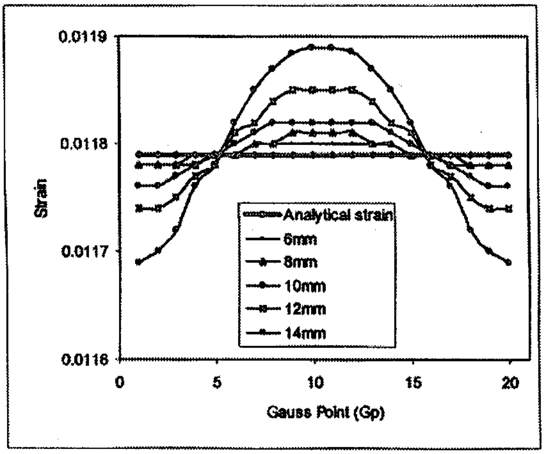

Figure 8. Influence Of Gripping Length On Longitudinal Strain Distribution.

tors given in Table 1 can be used to divide the measured strain in the evaluation of analytical strain from numerical or (more relevantly) experimental strain results for shorter lengths. It should be noted that these factors apply only to a straight sided coupon with a width of 10mm (equivalent aspect ratios also apply).

5. CONCLUSIONS

The shape of a short tensile test coupon has been established under a length constraint using the finite element method. A finite element model of the ASTM D3039 coupon has been established to validate the numerical coupon representation and to provide a benchmark against which the performance of the short coupon may be measured. Assuming a length of 50mm, the shape of this shortened coupon has been changed and assessed, leading to the specification of a plan geometry. The following principal conclusions have been drawn:

- The finite element method has been successfully applied to model the strain distribution of axially loaded short coupons for the determination of elastic material constants.
- Coupon length has been identified as an important geometrical parameter in the definition of a coupon test specimen. For specimens having a length of less than 60mm, the magnitude of the possible error between true and calculated strains has been estimated and an appropriate correction factor (acting on the measured strains) derived.
- Gripping length has been predicted not to significantly compromise the uniformity of the strain distribution in the central region of the short coupon. However, this parameter has been found to become significant in the determination of the material strength. A minimum gripping length of 8mm has been recommended depending on available coupon length and strength of the test material.
- A straight-sided short coupon, 60mm in length, 10mm in width 10mm gripping lengths has been shown numerically to be an effective shape in cases where insufficient material is available to provide a standard specification coupon (ASTM D3039). The uniformity of the strain field has been used to measure effectiveness.

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