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A New Approach for Investigation of Mode II Fracture Toughness in Orthotropic Materials

Abstract

Estimation of mode II fracture toughness (K_{IIC}) in composite materials is known as a troublous and crucial problem. Dissipated values of K_{IIC} that are reported in different fracture mechanics references is the evidence of the mentioned claim. This problem can signify the necessity of modification on common test methods and fixtures. The present study focuses on the causes of shear test results scattering in composite materials and presents some solutions in the form of necessary corrections that should be performed on the common test fixtures. Mixed mode I/II fracture limit curves are employed to show that the scattering in test results have strong relation with the creation of a considerable Fracture Process Zone (FPZ). It is shown that common test fixtures are blind in confrontation with FPZ and are not able to active toughening mechanisms in pure mode II, correctly. Therefore, estimation of K_{IIC} with available test fixtures has considerable standard deviation. After that, by employing some structural modifications on common fixtures, a new scheme of a shear fixture is proposed that in addition to include the FPZ effects, prepare suitable condition in order to activate the mode II toughening mechanisms. In this regard, it could be found that by applying these reforms, shear load concentration as well as the accuracy of empirical test and repeatability and reproducibility are enhanced. Furthermore, a 3D finite element method (FEM) was considered as the numerical method in which the Iosipesque and new fixture's specimens were analyzed by ANSYS software. It was found that by applying major amendments in the new shear test fixture, a remarkable precision in results can be obtained in comparison with the previous Iosipesque one

Keywords

Fracture Process Zone; Shear Test Fixture; Mode II Fracture Toughness; Composite Material; FEM

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Nomenclature	
Ema	The Efficiency Of Assembly
Nmin	Number Theory
Tmax	Total Time
Ta	Constant
x	Read The Value In The Chart
S	Average Standard Deviation
$\overline{x}$	Average Curves
N	Number Of Trials
L1	The Amount Of Deviation From The Diagram Without Distortion
L0	The Amount Of Deviation Of The Chart Origin
α	Symmetry Constant
D	Cell Deviation
P	The Number Of Laboratories
$S_{\overline{x}}$	Standard Deviation Of Cell Averages
S_r	Repeatability Standard Deviation
S_R	Reproducibility Standard Deviation
$(s_R)^*$	Provisional Of Reproducibility Standard Deviation
H	The Between-Laboratory Consistency Statistic
K	The Within-Laboratory Consistency Statistic
β	Symmetry Constant
$\overline{E}, \overline{G}$	Elastic And Shear Modulus Of Damaged Zone
T_M, T_m	The Strength Along And Across The Fiber Direction
K_I, K_{II}	Mode I And II Stress Intensity Factor
K_{IC}, K_{IIC}	Mode I And II Fracture Toughness
E, G	Elastic And Shear Modulus
v	Poisson's Ratio
$\overline{E}, \overline{G}$	Elastic And Shear Modulus Of Damaged Zone
$\overline{v}$	Poisson's Ratio Of Damaged Zone
β_i	Coefficient Depends On Elastic Properties
c_{ij}	Compliance Matrix
ρ	Orthotropic Damage Factor (ODF)
ζ	Location Vector
C_R, C_{RL}	Extensional And Sliding Compliance
$v_{ij}, i,j = L,R,K$	Poisson's Ratio On An Orthotropic Plane
$G_{ij}, i,j = L,R,K$	Shear Modulus On An Orthotropic Plane
$E_i, i = L,R,K$	Elasticity Modulus
τ	Shear Stress
P	Force
w	Specimen Width
t	Specimen Thickness

1 INTRODUCTION

Availability of reliable information related to different material properties for composite materials is mandatory for design and analysis purposes due to widespread application of these kind of materials in different industries. Fracture toughness of a material is one of the most applied properties in analysis of cracked structures. One of the most challenging problems is raised when estimating shear strength and mode II fracture toughness of the composite materials. Wrong estimation of fracture toughness may lead to catastrophic failures. Although several researches have been made for estimation of mode I fracture toughness (Ayatollahi and Sedighiani 2012), there is an insufficient evidence for evaluation of mode II fracture toughness (K_{IIC}). On the other hand, determination of mode II fracture toughness of orthotropic materials has been a serious concern in fracture mechanics (Gu et al. 2015).

Nowadays there are reliable fixtures and test methods for investigation of mode I fracture toughness of composite materials. Over the years, many techniques have been developed for measuring the fracture behavior of anisotropic materials (e.g. fiber reinforced composites) under different loading conditions (Recommendation 1985, Shen et al. 2012). In this way, K_{IC} and K_{IIC} are two parameters which have significant role for describing the fracture behavior of materials. Double Cantilever Beam (DCB) specimen (Devitt et al. 1980, Davidson et al. 1995, De Moura et al. 2008), wedge splitting and three-point bending (Reiterer et al. 2002, Vasic and Smith 2002), were typically experimental techniques which used to study the mode I fracture toughness, whereas, the End Notched Flexure (ENF), the End Loaded Split (ELS) specimens were used in measuring pure mode II fracture toughness (Carlsson et al., 1986, Chai 1990, Hashemi et al. 1990). Moreover, the beam specimens including Single Edge Notched Beam (SENB) (Hunt and Croager 1982, Russell and Street 1982, Mall and Mol 1991), Double-Edge Notched Beam (DENB) (Murphy 1979), Center Slit Beam (CSB) (Murphy 1988) and mode II end-loaded split cantilever beam (Vanderkley 1981) are often utilized to determine mode II fracture toughness for some metallic, wood and composite materials. For mixed mode loading conditions, the Single Leg Bending (SLB) specimen (Davidson et al. 1995) and cracked Brazilian Disc specimen (BD) (Sistaninia and Sistaninia 2015) have been employed for moderate crack tip mode mixity. To cover the entire range of crack tip mode mixity, all or some of these specimens have to be used (Rybicki et al. 1987, Polaha et al. 1996). Other researchers have designed special techniques (e.g. the Arcan) to cover the entire range of mode mixity (Arcan et al. 1978, Jurf and Pipes 1982, Donaldson 1985, Yoon and Hong 1990). Iosipescu shear fixture, primarily applied for measuring the shear strength of metal bars within the last 40 years. Within the years, it attended by the association of composite materials. The Iosipescu specimen was originally proposed for the shear strength measurement of metals by Nicolae Iosipescu (Iosipescu 1967) in the 1960's. In the 1983, Walrath and Adams were the first ones whose research was widely used in composite's specialized laboratories (Arcan 1984, Walrath and Adams 1984). They investigated the state of stress in a Iosipescu shear test specimen utilizing a finite element program. In 1984, the Iosipescu shear test fixture was redesigned by Walrath and Adams to incorporate several improvements (Walrath and Adams 1984). These improvements implied increase of fifty percent in size of specimen for easier measurement of shear strain. Also, a griping mechanism was used to achieve in relaxed strict tolerance on specimen width and a self-contained alignment tool during specimen installation was employed. Lee and Munro by the decision analysis technique evaluated the in-plane shear test methods for advanced composite materials (Lee and Munro 1986). Barnes et al. applied the Iosipescu shear test for measuring the shear properties of a unidirectional lamina, experimentally (Barnes et al. 1987). To this end, the shear strength and shear stiffness of glass reinforced polyester material, were measured using specimens with two different fiber orientations (Barnes et al. 1987). Acoustic emission was performed for monitoring a fractographic study, experimentally and also a finite-element analysis was conducted to evaluate the stress distribution within the specimen. Broughton and his colleagues (Broughton et al 1990) investigated the inter-laminar shear properties of unidirectional carbon-fiber reinforced epoxy and PEEK composites (Boothroyd 2005). In this regards, they evaluated the apparent shear strength and shear moduli using specimens with two different fiber orientations. Furthermore, Finite-element analysis was applied to determine the stress distribution within the Iosipescu specimen. An experimental and numerical investigation using conventional strain gage instrumentation and Moire Interferometry was performed in (Ho et al. 1993a). Farley evaluated the suitability of the Iosipescu specimen in the modified Wyoming fixture using finite element analysis and Moire Interferometry, to assess the uniformity of the shear stress field in the test section of graphite-epoxy composites (Ho et al. 1993a).

Almost simultaneously, in 1993, Ho et al. proposed a linear-elastic finite element analysis of the modified Iosipescu shear specimen according to the three fiber orientations (0°, 90° and 0°/90°) of Kevlar/and glass/epoxy composites (Ho et al. 1993b). They used a more realistic method for modeling of the load transfer between the fixture, specimen and the displacement conditions. In another study Pierron, and Vautrin presented new ideas of measurement of in-plane shear strengths of unidirectional carbon/epoxy composites from Iosipescu shear test

(Pierron and Vautrin 1998). In 2002, a theoretical evaluation of the applicability of the Iosipescu test was conducted by Chiang and He for crossbred composites instead of being arranged in a separate lamina (Chiang and He 2002). The V-notch specimen of hybrid composites was analyzed utilizing the Finite-Element Method (FEM) based on the fiber properties in order to evaluate the effect of varied microstructures in hybrids on the shear stress and strain states. Then in 2004, Xaviera et al. investigated the applicability of the Iosipescu and off-axis test methods for the shear characterization of clear wood in both experimentally and numerically approach (Xavier et al. 2004). Although, they applied Maritime Pine wood (Pinus Pinaster) to figure out the off-axis shear moduli, but due to structural inaccuracy, they could not detect the assumed properties precisely. In 2006, Melin and Neumeister, modified Iosipescu test utilizing a variable notch opening angle 0°, depending on the material anisotropy and orientation (Melin and Neumeister 2006). They claimed that, modified Iosipescu test can measure shear properties further accurately, more completely, and with fewer sources of error. But the inaccuracy was not omitted, completely. Bradley et al. examined the in-plane and inter-laminar shear properties of a 2D PAN-CVI carbon/carbon composite whose reinforcement layers were formed from a non-woven duplex cloth to a short fiber felt layer (Bradley et al. 2007). This study also provided an opportunity to evaluate the Iosipescu test methodology when applied to this type of carbon/carbon composite. In 2008, Melin presented modified version of Iosipescu shear test, utilizing a variable notch opening angle that accommodates both anisotropic materials and their orientation (Melin and Neumeister 2006). In 2009, Manal et al. according to application of new-generation composites in a structural beam, such as sandwich beam made up glass fiber skins and modified phenolic core material, investigated the in-plane shear behavior. Based on the results of this study, the asymmetrical shear test was recommended as a test method for determining the shear properties of sandwich structures with high strength core materials (Manalo et al. 2010).

Hufenbach et al. in 2011, focused on the examination of the 3D shear damage behavior, and its phenomenological failure process of a thermoplastic composite made of E-glass/polypropylene hybrid with a woven reinforcement (Hufenbach et al. 2011). They derived modeling strategies and performed within the Ls-Dyna FE software.

In 2013, Sun et al. established guidelines for preparing shear tests of ceramic-fiber-reinforced Aerogel. They presented a finite element analysis on Iosipescu specimens with different V-notches and round-notch configurations (Sun et al. 2013). In this regard, Osei-Antwi performed an experimental study utilizing Iosipescu specimens to evaluate the effects of parameters such as shear plane, density and adhesive joints on the shear stiffness and strength of Balsa wood panels (Osei-Antwi et al. 2013). In 2015, Catalanotti and Xavier proposed a modified Iosipescu specimen to measure the mode II fracture toughness and the corresponding crack resistance curve of fiber-reinforced composites (Catalanotti and Xavier 2015). They employed numerical analysis and empirical test that performed on IM7/8552 material.

As it could be found from the above literature, there is not presented a reliable fixture and well defined role for investigation of mode II fracture properties of composite materials. Therefore, in application field the designer will encounter to contradictory reported information in scientific sources for fracture properties of composite materials. In the present research, using mixed mode I/II fracture limit curves in composite materials, strong dependency of mode II fracture toughness on created crack tip fracture process zone is proved. Therefore, evaluation of shear properties in composite materials demands a nonlinear process. In fact, the main problem in achieving attributable test results from common shear test fixtures is due to debility of them in nonlinear fracture mechanics applications. Accordingly, for evaluation of mode II fracture toughness in composite materials, a fixture is needed that can estimate the nonlinear process activated in crack tip vicinity. In this paper, inspired by the mode I wedge splitting test fixture (Vasic and Smith 2002) that has the ability of considering FPZ effects, well known Iosipescu shear test fixture is modified to estimate the latent energy in created mode II process zone. In this regards, both of the tradition and modified fixture are manufactured and examined, individually. Accordingly, some designing modification has been done and advantages of modified fixture in comparison with tradition one, are investigated. Furthermore, accuracy of measured shear load has been improved due to reduction of standard deviation. In this regards, a statistical method in accordance with E-691 ASTM (1999) standard is employed for both new and earlier fixtures in order to reach accurate investigation. Eventually, it is shown that, by employing modifications; favorable results are achieved by the new fixture scheme in comparison with previous one. For this purpose, glass/epoxy & graphite/epoxy, wood and PMMA specimens are prepared and examined as orthotropic, transversely isotropic and isotropic materials, respectively. It is figured out that by considering FPZ, modified shear test fixture has remarkable precision and capability in comparison with traditional one. On the other hand, more precision in FPZ evaluation at the crack tip vicinity causes more accuracy in K_{IIC} results.

2 PRINCIPAL FACTORS AFFECTING ESTIMATION OF K_{IIC}

In this section, utilizing common mixed mode I/II fracture limit curves (Anaraki and Fakoor 2010b) the nature of KIIC is described for composite materials. As it well known, the fracture phenomenon of composite materials is along with creation of considerable damage zone in crack tip vicinity. This damaged area also called as Fracture Process Zone (FPZ) and contains multitude of micro cracks which causes difficulties in estimation of shear behavior and therefore KIIC. Figure 1 demonstrates the FPZ growing region by developing shear load condition.

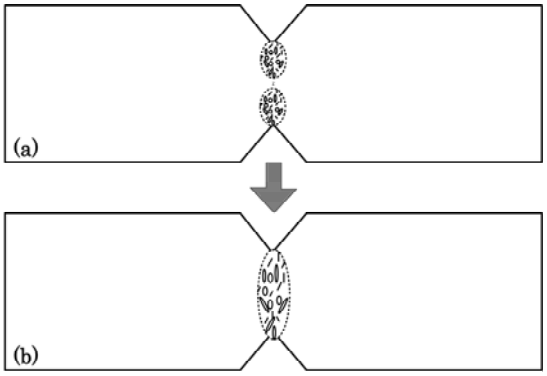


Figure 1: *(a) & (b) initiation and propagation of FPZ in the Iosipescu shear test specimen, respectively.*

Although based on experimental observations (Mall and Mol 1991), FPZ in mode II loading condition is large and narrow, in mode I appear as small and insignificant area (Figure 2).

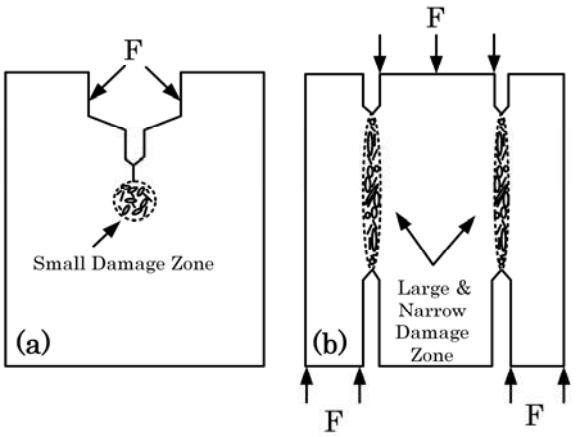


Figure 2: *(a) & (b) indicate the FPZ in mode I & mode II, respectively.*

Although, the evaluation of KIIC has significant role in mode II fracture properties, it used to be a serious concern encountering to fracture mechanics of orthotropic materials up to know (Gu et al. 2015). The main reason of difficulty is related to the measurement of the observed energy in created fracture process zone at the crack tip vicinity.

In this regards, a KIIC mathematic dependency to the FPZ can be demonstrated as follows. As it well known, a general form for mixed mode I/II fracture of orthotropic materials could be expressed as follows (Anaraki and Fakoor 2010b):

$$K_I^{\,2} + \rho K_{II}^{\,2} - K_{Ic}^2 = 0 \tag{1}$$

In which, ρ, KIC, KII and KI are damage parameter (Anaraki and Fakoor 2010b), mode-I fracture toughness, mode-II and mode-I stress intensity factors, respectively. Equation 2 shows an elliptical region that the limits are mode I and mode II fracture toughness (Figure 3).

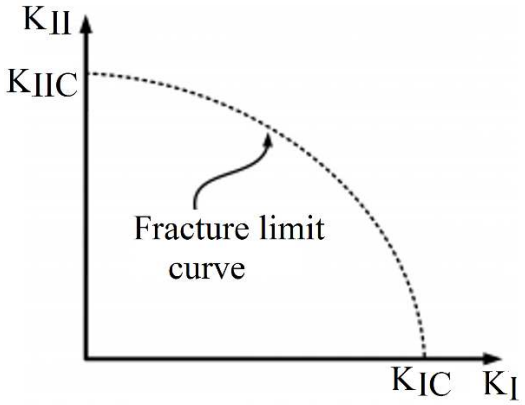


Figure 3: *Typical fracture limit curve for a composite material*

Therefore, for pure mode-II the equation (1) will return fracture toughness of mode II as follows:

$$K_{IIc} = \frac{K_{Ic}^2}{\rho} \tag{2}$$

Equation 2 emphasizes on strong dependency of mode II fracture toughness on damage zone parameter ρ. Therefore, considering reliable test fixtures for mode I fracture toughness, it could be concluded that scatter in reported values for KIIC of orthotropic materials raised form the blind estimation of FPZ effects. On the other hand, in design of available test specimens, the effects of FPZ are not considered properly and the standard deviation in test results is considerable. Hence, for accurate estimation of KIIC, we proposed two different approaches:

I. Implicit approach: that is based on investigation of fracture process zone and estimation of damage parameter ρ.

II. Explicit approach: that signifies a new test fixture design, in which FPZ energy could be estimated. At the following sections, these two mentioned approaches have been investigated.

3 IMPLICIT APPROACH

Considering the first approach, some experimental and theoretical formulations for damage factor ρ, have been proposed in Table 1 and 2.

Table 1: *experimental mixed mode I/II fracture criteria for orthotropic materials and their related damage factor.*

Author/year	Fracture criterion	Damaged parameter	KIIC
Wu (1967)	$K_I + \left(\frac{K_{Ic}}{K_{IIc}^2}\right) K_{II}^2 - K_{Ic} = 0$	$\rho = \left(\frac{K_{Ic}}{K_{IIc}^2}\right)$	$K_{IIc} = \left(\frac{K_{Ic}}{\rho}\right)^{\frac{1}{2}}$
Leicester (1974)	$K_I + \left(\frac{K_{Ic}}{K_{IIc}}\right) K_{II} - K_{Ic} = 0$	$\rho = \left(\frac{K_{Ic}}{K_{IIc}}\right)$	$K_{IIc} = \left(\frac{K_{Ic}}{\rho}\right)$
Williams and Birch (1976)	$\frac{K_I}{K_{Ic}} = 1$	----	----
Hunt, Croager (1982)	$K_I + \left((1.005)\frac{K_{Ic}}{K_{IIc}^{3.4}}\right) K_{II}^{3.4} - 1 = 0$	$\rho = \left((1.005)\frac{K_{Ic}}{K_{IIc}^{3.4}}\right),\ m=1,\ n=3.4$	$K_{IIc}^{3.4} = \left((1.005)\frac{K_{Ic}}{\rho}\right),\ m=1,\ n=3.4$
Mall et al. (1983)	$K_I + \left(\frac{K_{Ic}}{K_{IIc}^2}\right) K_{II}^2 - 1 = 0$	$\rho = \left(\frac{K_{Ic}}{K_{IIc}^2}\right),\quad m=1, n=2$	$K_{IIc}^{3.4} = \left((1.005)\frac{K_{Ic}}{\rho}\right),\ m=1,\ n=3.4$

Table 2: *Common theoretical mixed mode I/II analytical facture criteria for orthotropic materials and related damage factor.*

Author/year	Fracture criteria	Damage parameter	pure mode-II fracture toughness
Jernkvist (2001a)	$K_I^2+\beta_1 K_{II}^2-K_{Ic}^2=0$	$\rho=\beta_1=\left(\frac{K_{Ic}}{K_{IIc}}\right)^2=\frac{E_I'}{E_{II}'}=\sqrt{\frac{C_{11}'}{C_{22}'}}$	$K_{IIc}=\frac{K_{Ic}}{(\rho)^{\frac{1}{2}}}$
Jernkvist (2001a)	$K_I^2+\beta_2 K_{II}^2-K_{Ic}^2=0$	$\rho=\beta_2=\left(\frac{K_{Ic}}{K_{IIc}}\right)^2$	$K_{IIc}=\frac{K_{Ic}}{(\rho)^{\frac{1}{2}}}$
Jernkvist (2001a)	$\frac{1}{(\beta_3+\sqrt{\beta_4})}[\beta_3 K_I+\sqrt{\beta_4 K_I^2+K_{II}^2}]-K_{Ic}=0$	$\beta_3+\sqrt{\beta_4}=\frac{K_{IIc}}{K_{Ic}}$	$K_{IIc}=\left(\beta_3+\sqrt{\beta_4}\right)K_{Ic}$
Romanowicz and Seweryn (2008)	$K_I^{\ 2}+\frac{c_{RL}}{c_R}K_{II}^{\ 2}=K_{Ic}^2$	$\rho=\frac{c_{RL}}{c_R}=\left(\frac{K_{IC}}{K_{IIc}}\right)^2$	$K_{IIc}=\frac{K_{Ic}}{(\rho)^{\frac{1}{2}}}$
Anaraki, Fakoor (2010b)	$K_I^2+\rho K_{II}^2-K_{Ic}^2=0$	$\rho=\frac{(5-\nu)(\xi\sqrt{\lambda}+\nu_{LR}\lambda)^2}{(10-3\nu)(1+0.5\nu_{LR}(1+\lambda))^2}$	$K_{IIc}=\frac{K_{Ic}}{(\rho)^{\frac{1}{2}}}$
Anaraki, Fakoor (2010a)	$K_I^2+\rho K_{II}^2-K_{Ic}^2=0$	$\rho=2\left[\left(\frac{T_m}{T_M}\right)+\left(\frac{T_m}{T_M}\right)^2\right]$	$K_{IIc}=\frac{K_{Ic}}{(\rho)^{\frac{1}{2}}}$
Fakoor, Mehri Khansari (2016)	$K_I^2+\rho K_{II}^2-K_{Ic}^2=0$	$\rho=\frac{\bar{E}}{\bar{G}}=\frac{E\left[1+\frac{16(1-\bar{\nu}^2)(10-3\bar{\nu})w}{45(2-\bar{\nu})(1-\gamma w)}\right]}{G\left[1+\frac{32(1-\bar{\nu})(5-\bar{\nu})w}{45(2-\bar{\nu})(1-\gamma w)}\right]^{-1}}$	$K_{IIc}=\frac{K_{Ic}}{(\rho)^{\frac{1}{2}}}$

In which, β_i, C_{ij} and ζ are coefficients depending on elastic properties, compliance matrix and location vector, respectively. also, C_R, C_{RL}, ν_{RL}, ν and λ_{ij} are the extensional and sliding compliance characterizing wood weakened by micro-cracks oriented in the orthotropic plane of normal r, Poisson's ratio on an orthotropic plane of normal r, Poisson's ratio of non-cracked body and coefficients in the non-local stress fracture criterion, respectively (Anaraki and Fakoor 2010b). Also, Tm and TM are the strength along and across the fiber direction, respectively (Romanowicz and Seweryn 2008). In addition, E_I' and E_{II}' are generalized elastic moduli and defines as (Jernkvist 2001b):

$$\begin{aligned}
&E_I'=\left[\frac{C_{11}'C_{22}'}{2}\left(\sqrt{\frac{C_{22}'}{C_{11}'}}+\frac{2C_{12}'+C_{66}'}{2C_{11}'}\right)\right]^{-1/2}\\
&E_{II}'=\left[\frac{C_{11}'^2}{2}\left(\sqrt{\frac{C_{22}'}{C_{11}'}}+\frac{2C_{12}'+C_{66}'}{2C_{11}'}\right)\right]^{-1/2}\\
&C_{kl}'=C_{kl}-C_{k3}C_{l3}/C_{33}
\end{aligned}\tag{3}$$

Where, k=1,2 and l=1,2.

Although, there are widespread researches for determination of damage parameter ρ, there is insufficient experimental approach for determination of FPZ characteristics, properly. In present research, damage parameter has been investigated based on tensile and shear compliance of the damaged zone material.

$$\rho=\frac{(1/\bar{G})}{(1/\bar{E})}=\frac{\bar{E}}{\bar{G}}\tag{4}$$

In which, $\bar{E}$ and $\bar{G}$ are defined as modulus of elasticity and shear modulus of damage zone, respectively. Therefore, generalized experimental fracture toughness for pure mode II could be rephrased as follows:

$$K_{IIc} = \left(K_{Ic}\right)\left(\frac{\bar{G}}{\bar{E}}\right) \tag{5}$$

Although, estimation of KIIC by this approach is completely staid, but calculation of damage zone material properties is very crucial. Some test setup and specimens are already introduced for estimation of damage zone properties (Anaraki and Fakoor 2010a). Also some theoretical approaches have been introduced for calculation of damage moduli of elastic solids (Horii and Nemat-Nasser 1983, Fakoor and Mehri Khansari 2016).

4 EXPLICIT APPROACH

This approach is based on presentation of experimentally modified shear test fixture that is capable to include the effects of FPZ as well. The modifications were performed on Iosipescu shear test fixture due to widespread application of the fixture for composite materials.

4.1 SHEAR TEST CONFIGURATION & TESTING METHOD

As it well known, the traditional configuration of shear test fixture called "Iosipescu" has been utilized for many years. The Iosipescu shear method was standardized by ASTM in 1993 (ASTM, 1993). The fixture has been employed extensively by the composites testing community since the mid-1980s. In its quarter-century of use, it has proven to be accurate and reliable (Walrath and Adams 1984). Take into account of Iosipescu configuration, general form and testing method of the traditional Iosipescu fixture has been discussed as follows (Figure 4).

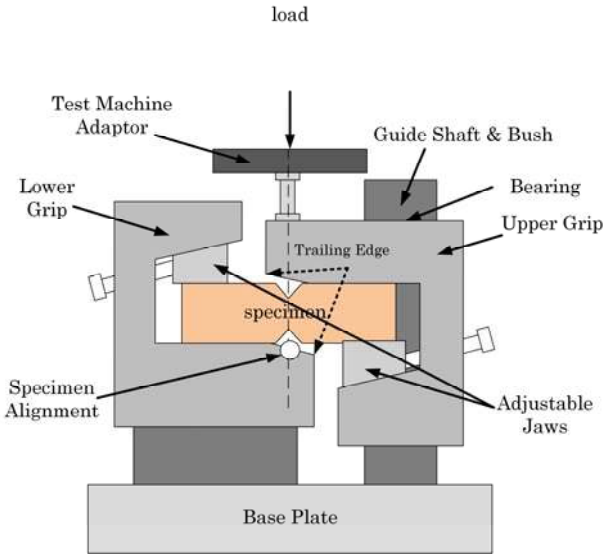


Figure 4: *The components and configuration of the Iosipescu fixture*

Components and configuration of the Iosipescu has been illustrated in Fig.4. As it is shown, the fixture is consisting of 35 component including; baseplate, guide shaft, bush, lower and upper grip, bearing post, adjustable jaws, specimen alignment pin and loading pad (Walrath and Adams 1984). The fixture aims to produce a state of pure shear stress in the region called "shear zone" between the notches by applying two counteracting force couples to the specimen. The average shear stress, τ , in the specimen gage section was obtained from the load, P, applied by the testing machine and the specimen cross-sectional area between the notches (Eq. 6) (Bradley et al. 2007).

$$\tau = \frac{P}{wt} \tag{6}$$

In which, w is the distance between the notches and t is the specimen thickness. As it shown in Eq.6, in order to have a precision shear stress, complete transmission of applied load to the specimen should be done. In this regard, effect of some components like grip angle, grip height and guide bush is investigated. These experimental tests were applied on graphite/epoxy; PMMA and Western White Pine wood. Also, specimens were cut in the required orientation from a composite block of the appropriate lay-up, then milled and ground to the final dimen-

sions specified by ASTM D 5379 (ASTM 1999). Western white pine wood was prepared in direction of wood's tracheid. Three specimens are prepared for each material type (**Figure 5** and **6**).



Figure 5: *universal compression test machine (STM-150)*

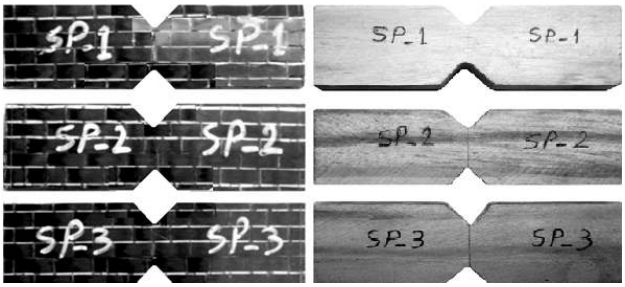


Figure 6: *Graphite-epoxy composite and wood specimens*

Force versus extension diagrams have been shown in Figure 7, Figure 8 and Figure 9, which are related to graphite/epoxy, Western white pine wood and PMMA respectively.

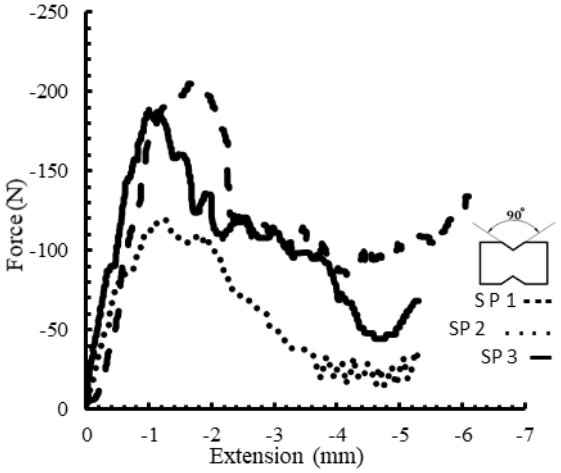


Figure 7: *graphite/epoxy plotted by the Iosipescu fixture.*

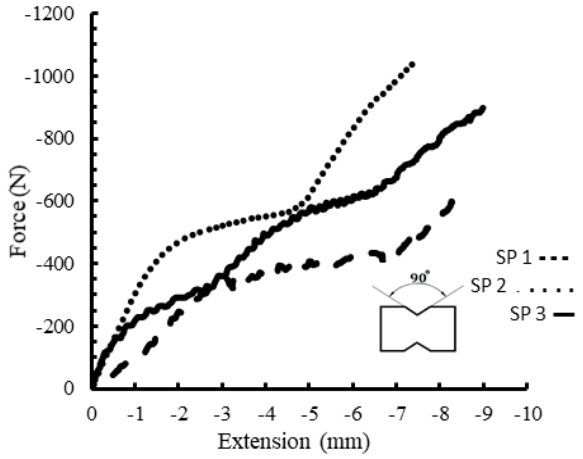


Figure 8: *Western white pine wood examined by the Iosipescu*

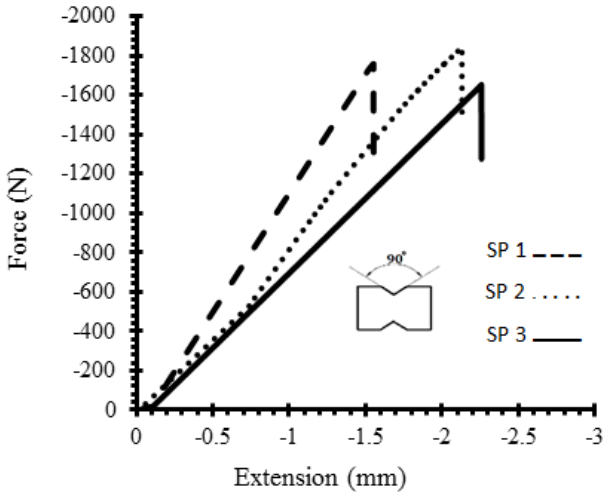


Figure 9: *PMMA examined by the Iosipescu*

It can be figured out that the plot trend of force-extension curves for graphite/epoxy and wood test specimens are very different; whereas, the trend of force-extension curves for PMMA are the same. The main reason of this diversity comes from creation of Fracture Process Zone (FPZ) at crack tip vicinity of orthotropic materials. This area usually could be investigated by Scanning Electron Microscopy (SEM) as shown in Figure 10.

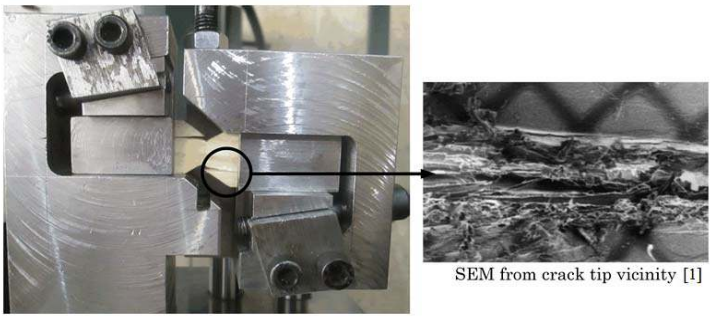
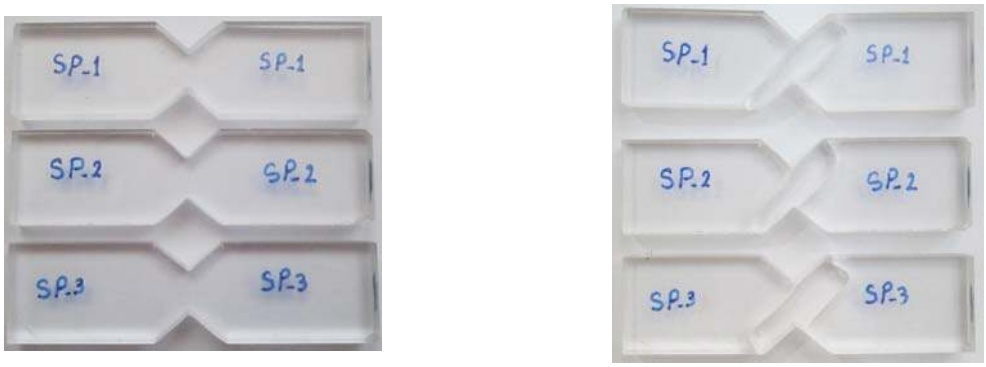


Figure 10: *SEM photo from crack tip vicinity of wood specimen*

On the other hand, for isotropic materials (such as PMMA), due to negligible FPZ, the scatter in test results is acceptable (see Figure 11), so Iosipescu shear test fixture could be utilized for these types of materials as well.



(a) (b)

Figure 11: *PMMA test specimen (a) and (b) indicate the before and after test, respectively.*

Therefore, SEM photos taken from composite test specimens show that the assumed fixture is not able to activate the nonlinear fracture mechanisms (such as bridging and micro cracks) in FPZ. In the following, a modified configuration for this fixture is introduced. In the modified case we have tried to redesign the available Iosipescu shear test fixture to create stable FPZ pattern.

4.2 MODIFIED CONFIGURATION & TESTING METHOD

In this section a modified shear test fixture based on the Iosipescu fixture is proposed. The main purpose of these modifications is conducting the shear stress flow in to a narrow process bond (see **Figure 2**) and creation of a repeatable pattern for test specimens. To this aim, some structural bugs in the common Iosipescu fixture which lead to dissipation of stress flow in FPZ were found, experimentally as follows:

Collisions between the trailing edge and specimen (Figure 12),

Rotating of the grip due to inconvenience number and position of the guide shaft (Figure 13), and

Collisions between the upper grip and the base plate during long displacement

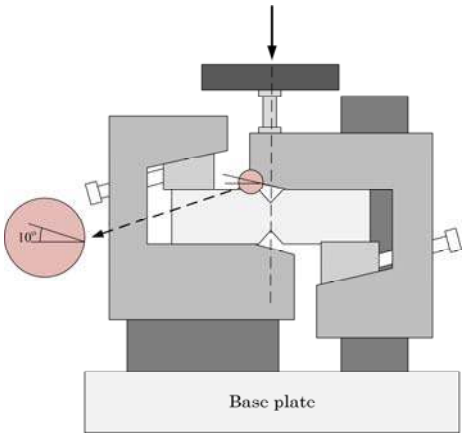


Figure 12: *Collisions between the trailing edge and specimen*

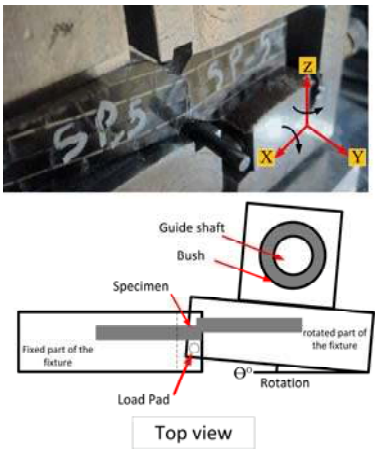
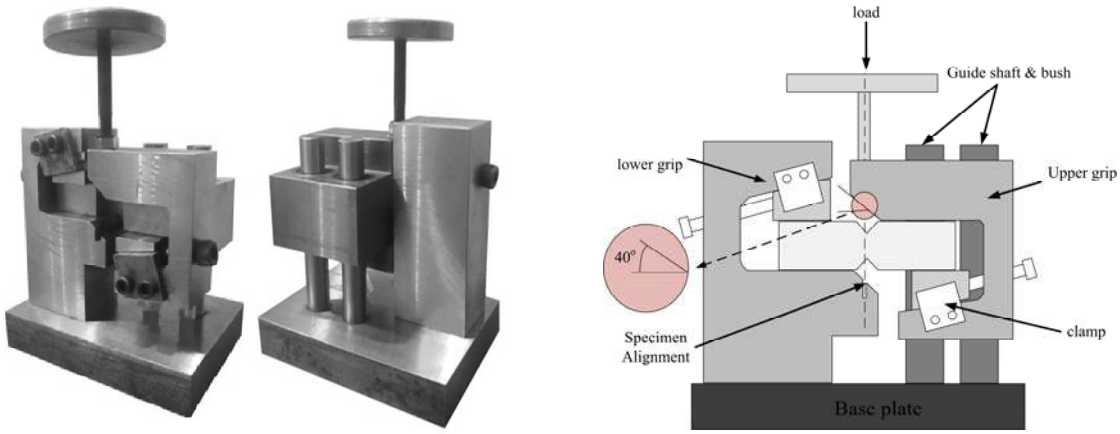


Figure 13: *unbalancing in specimen due to upper grip rotation (around assumed Z and X axis)*

These crucial bugs that were found by a try and error process, greatly effect on the final results. The related modifications are as follows:

Lower grip altitude was changed from 96 mm to 110 mm,
Two guide shafts were utilized instead of one due to grip rotation preventing
Trailing edge angle due to clash preventing was changed from 10º to 40º
Number of fixture components based on DFMA principal was reduced to 27 parts and two special clamps were performed to fix specimen.

Eventually, by applying these modifications, the final configuration of the Modified shear test fixture was constructed as Figure 14(a), (b).



(a) (b)

Figure 14: *real (a) & schematic (b) view of modified shear fixture*

Force-extension diagrams have been extracted for new case of designed shear fixture, the results are shown in **Figure 15**, **16** and **17**.

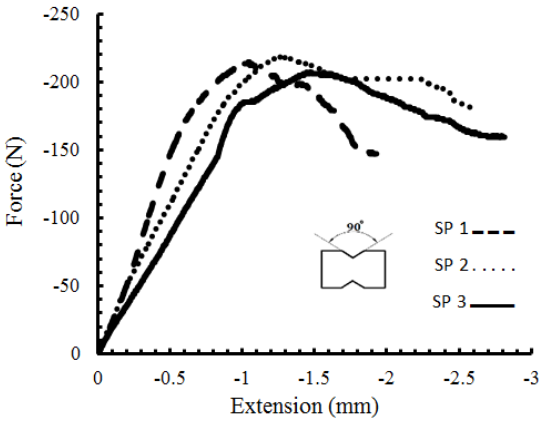


Figure 15: *graphite/epoxy plotted by the modified fixture*

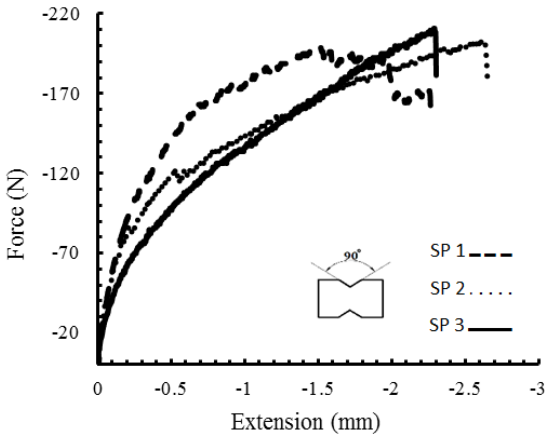


Figure 16: *Western White Pine wood examined by the modified fixture*

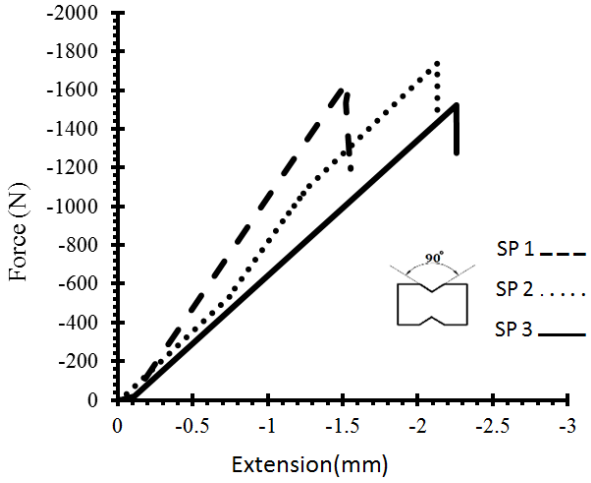


Figure 17: *PMMA examined by the modified fixture*

Furthermore, the related SEM photos were taken from creation of FPZ in new designed fixture (See **Figure 18**).

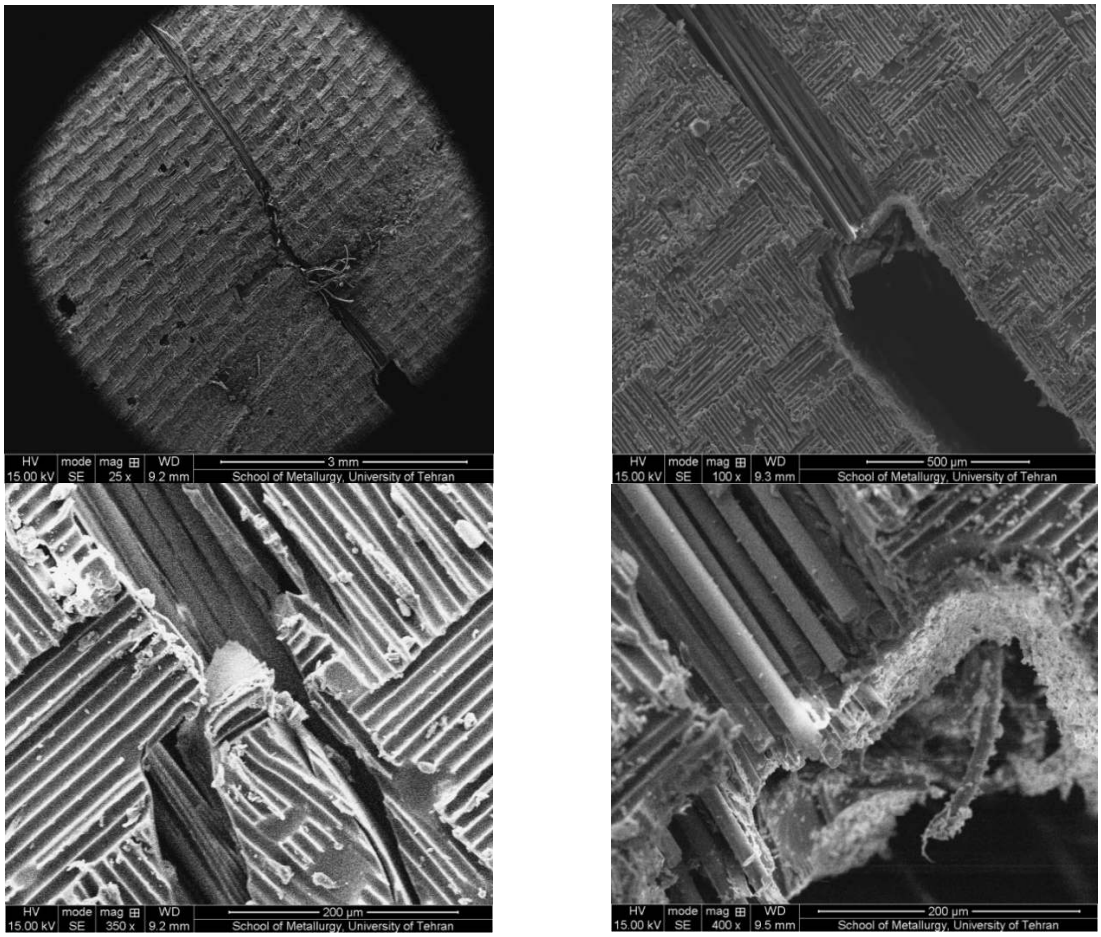


Figure 18: *SEM photos that are related to creation of FPZ in glass/epoxy*

As it could be found, the same FPZ pattern is achieved from the new designed fixture due to creation of narrow shear stress bond.

5 FINITE ELEMENT ANALYSES

5.1 NON-CRACKED BODY ANALYSIS

As it well known, the finite element analyses (FEM) is a reliable approach for analyzing the shear fixture specimens. In this stage, performances of Iosipesque and new shear fixture were studied, numerically. In this regard, three dimensional finite element models of Iosipesque and new fixture's specimens were prepared and analyzed in FEM software (ANSYS software). The models were meshed using C3D20 elements. Also, 9604 elements considered in the shear specimen. The typical 3D mesh pattern generated for the standard shear specimens (**Figure 19**).

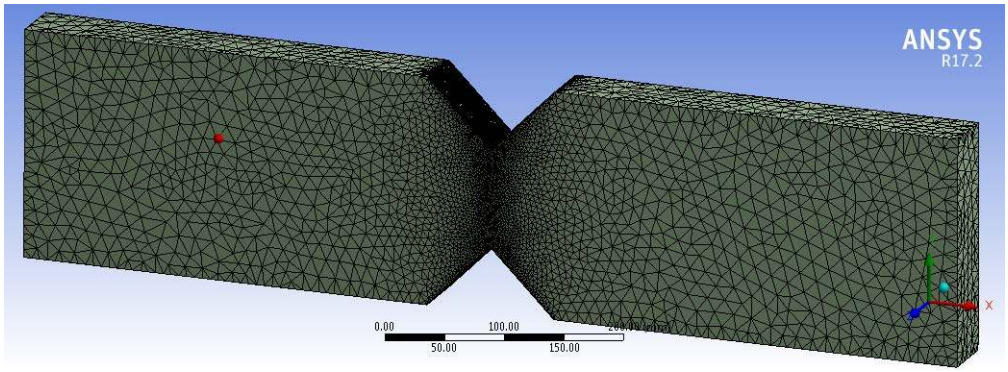


Figure 19: *Typical 3D mesh pattern generated for the standard shear specimens (ANSYS)*

Moreover, the geometrical dimensions and material properties are presented in **Table 3**.

Table 3: *Geometrical dimensions and material properties given of the standard shear specimens*

Quantity	Value
Length	76 mm
Wide	20 mm
Thickness	3 mm
Young's modulus	70 GPa
Poisson's ratio	0.3

Furthermore, all of the displacements and rotational components (except the y displacement component of right support) considered as the boundary condition. **Figure 20** indicates the shear stress distribution for both the Iosipesque and new shear test specimens.

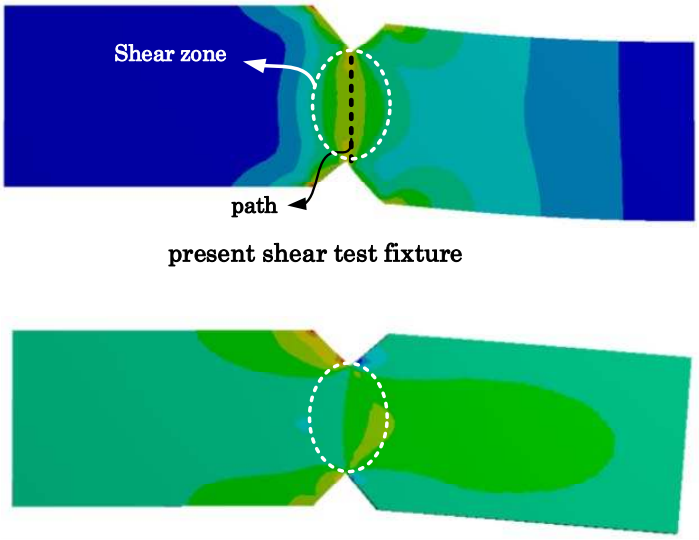


Figure 20: *Finite element results obtained for the shear stress in the Iosipesque specimens*

As it can be seen in **Figure 20**, due to the structural modification in new shear test fixture, distribution of shear stress between two v-notched regions in the new shear test fixture is more accurate than Iosipesque one. On the other hand, by applying the modifications, shear loads concentration, repeatability and reproducibility and also the standard deviation could be enhanced, precisely. It means that, scattering in the stress-strain diagrams can be declined, significantly. Therefore, the variations of shear stress and strain distribution can be investigated versus shear zone displacement (**Figure 21**, **Figure 22**) thorough the defined path in y direction.

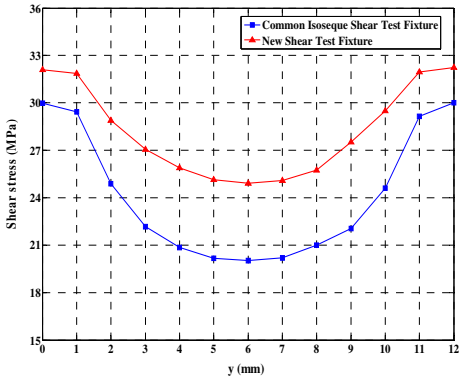


Figure 21*: Variations of shear stress thorough the path defined between two v-notched regions*

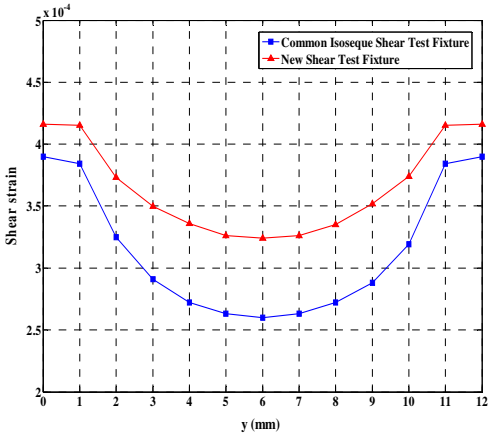


***Figure 22**: Variations of shear strain thorough the path defined between two v-notched regions*

It can be seen that, the values of shear stress and strain in the all points of defined path for new fixture is much more than common Iosipesque shear test fixture. Hence, it was figured out that fracture of specimen under certain load in new fixture seems to has more precision (due to the accurately stress flow distribution).

5.2 CRACKED BODY ANALYSIS

In this section, cracked body has been considered in comparison with non-cracked body in the shear specimen and real loads values applied on it. Furthermore, the type of crack was considered as pre-meshed and initiated by notch vertex. For better meshing control on cracked region, Tetrahedrons mesh was applied and total number of elements by considering mesh-sizing toolbox was calculated as 66210 (**Figure 23**).

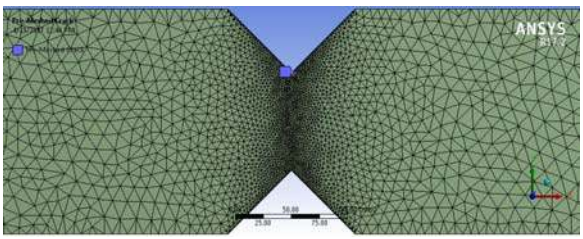


***Figure 23:** pre-cracked mesh creation in shear region*

Total deformation, maximum and equivalent stress are well-known output in FEM. **Figure 24** to **Figure 31** indicate the total deformation with maximum and equivalent elastic strain and stress for modified and Iosipesque shear test fixture in unidirectional E-glass/epoxy.

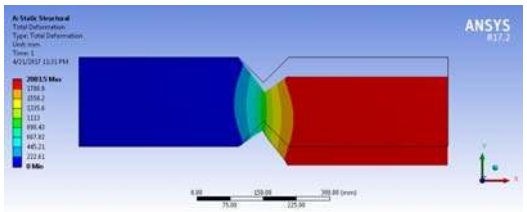


***Figure 24:** total deformation results for modified shear test fixture*

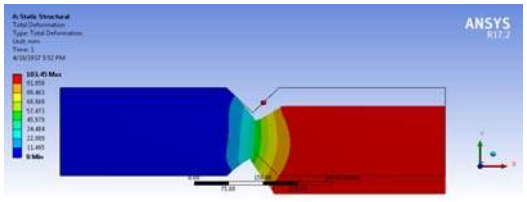


***Figure 25**: total deformation results for Iosipesque shear test fixture*

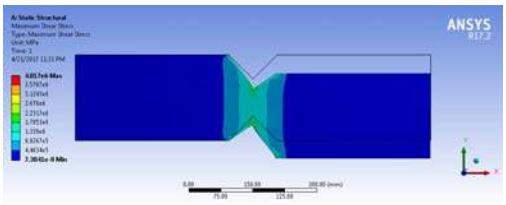


Figure 26: *maximum shear stress results for modified shear test fixture*

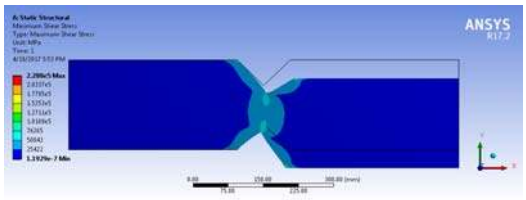


Figure 27*: maximum shear stress results for Iosipesque shear test fixture*

Similar to non-cracked body analysis, for cracked body section the evaluation of stress, deformation and even energy has been considered, properly. In this regard, all parameters have been evaluated thorough the defined path in y direction (**Figure 28** to **31**).

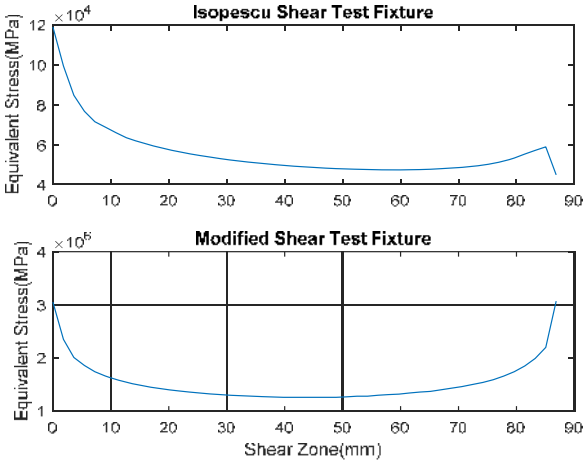


Figure 28*: comparison of equivalent stress in Iosipesque and modified fixture.*

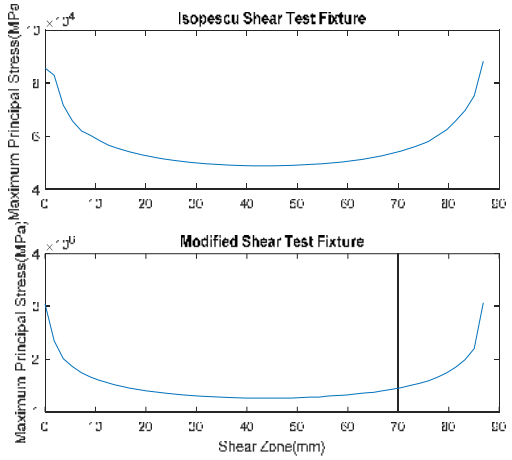


Figure 29*: comparison of maximum principal stress in Iosipesque and modified fixture.*

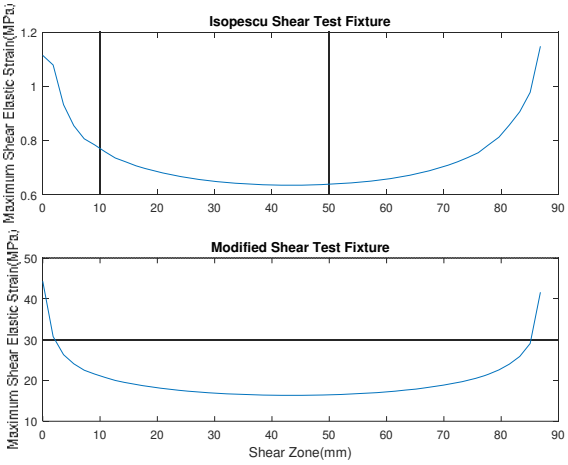


***Figure 30**: comparison of maximum shear strain in Iosipesque and modified fixture.*

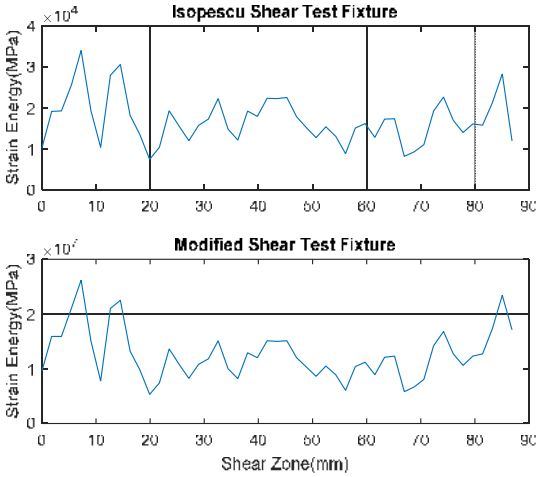


***Figure 31**: comparison of strain energy in Iosipesque and modified fixture.*

As it is mentioned in the above Figures, the amount of stresses and strains in the modified shear test fixture has more concerning with shear zone. On the other hand, toughening mechanisms can be better created in modified fixture in comparison with common one. The statement can be proved by localizing of strain energy in the middle of shear region. Furthermore, fracture parameters like the stress intensity factors (K_I, K_{II} and K_{III}) were evaluated in both modified and Iosipesque shear test fixture. At the following table, stress intensity factors and T-stress were checked and compared in both fixtures (**Table 4**).

***Table 4:** stress intensity factors and T-stress for both fixtures*

fixture	Material	Average K_I $(MPa.\sqrt{mm})$	Average K_{II} $(MPa.\sqrt{mm})$	Average K_{III} $(MPa.\sqrt{mm})$	T-Stress (MPa)
modified	Graphite/Epoxy	-6.0353e+006	-8.6137e+005	-7.335e+007	-3.4649e+006
Iosipesque	Graphite/Epoxy	-6.0353e+006	-8.6137e+005	-7.335e+007	-3.4649e+006
modified	PMMA	-6.0353e+006	-8.6137e+005	-7.335e+007	-3.4649e+006
Iosipesque	PMMA	-2.0336e+005	1.8968e+005	-3.8988e+006	-2.7485e+005
modified	Glass/Epoxy	-1.82E+05	1.44E+05	-1.34E+06	-1.29E+06
Iosipesque	Glass/Epoxy	-1.27E+05	1.90E+05	-1.70E+06	-1.85E+05

6 CONCLUSION

In the present study, by considering the wide spread published antithesis data in different references for shear properties of composite materials, two reliable approaches were introduced for estimation of shear load and mode II fracture toughness. To this aim, a deep study was performed for finding out of the nature of KIIC. Mixed mode fracture limit curves were used for this purpose. Strong relation between KIIC and fracture process zone was shown. Also, a modified shear test fixture based on structural modifications was proposed in order to

include the effects of FPZ. For this purpose, at first, common Iosipescu shear test fixture was examined and some structural bugs were found in a try and error process. In this way, some arbitrary composite materials like, glass/epoxy, graphite/epoxy and wood were investigated based on E-691 ASTM (1999) and DFMA principles . Then, a modified shear test fixture was proposed based on resolved bugs. The main purpose of these modifications was conducting the shear stress flow in to a narrow bond and creation of the same pattern for process zone in all test specimens. Furthermore, a 3D finite element method (FEM) was considered as the numerical method in which the Iosipesque and new fixture's specimens were analyzed by ANSYS software. It was found that by applying major amendments in the new shear test fixture, a remarkable precision in results can be obtained in comparison with the previous Iosipesque one.

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