Tensile Loading Rate Effect on Open-Hole Tensile Strength and Failure Mechanism of Polymer Composites

Sunny, K. K. Singh, and Ruchir Shrivastava

Abstract Glass fiber reinforced polymer composite used in advanced engineering exercise as a frame in the aviation and automobile industries is often exposed to circular holes to connect different components through joints such as a bolt joint. In this article, the tensile strength of symmetric GFRP laminates with an open hole, and its failure mechanism under uniaxial varying tensile loading rate (1, 10, 50, and 100 mm/min) was investigated. The specimens were produced using the hand-lay-up process. Samples were prepared in compliance with the ASTM D5766 standard and tested with a 50 KN load cell on a universal Hounsfield H50KS testing machine. A numerical model was developed with shell model 3D deformable and meshed with the S4R element. Numerical results were compared with experimental results. Results suggest that the maximum tensile strength of composite specimens with open hole increased as the loading rate increased, and the debonding of fiber is a highly dominant failure mechanism as compared to other failures. The maximum tensile strength of specimens with a higher loading rate (100 mm/min) is maximum and is comparatively 15.04% greater than in slower loading rate of 1 mm/min. The experimental data reveal that rate-dependent constitutive relationships are helpful in modeling polymer composites and are used to estimate the effective failure response of composites.

Keywords GFRP · Hole · Tensile strength · Loading rate effect · Numerical simulation

1 Introduction

Composite materials play a crucial role in the development of high-performance, lightweight structures in recent years [1]. Along with corrosion resistance, these materials offer high stiffness and a high strength-to-weight ratio. Which make it relevant in the field of aircraft, vehicles shipbuilding and housing goods [2]. They are

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also found extremely useful in an orthopedic surgical substitute for bone implants [3].

Joints can be adhesive-bonded, mechanically bonded using bolts, and combination of both [4]. The bonded joints provide a lightweight and a tight grip on the frame, but for the sealed surface, they need other conditions. Relatively, mechanically fastened joints do not need location surface preparation to reduce complexity, therefore such composites are exposed to open holes to link with several other parts [5]. These holes will interfere with the force flow in the path of the fibers and produce large quantities of stress around the hole area. This stresses the level around the hole in the available space for the failure of the components. This causes weakening of elements of the structure leading to complete failure. The rise in the use of GFRP laminates in the development of structural components with significant mechanical efficiency demands comprehensible explanation of the tensile nature of these composites with holes [6]. The literature suggests need of further investigations of these composites, when it succumb to higher loading rates [7].

Shokrieh and Jamal-Omidi [8] examined the mechanical behavior of GFRP composites at different uniaxial strain rate (0.0017, 0.55, 5.6, 46, and $85s^{-1}$). The results of the experiment showed an increase of 51.52%, 11.83%, 8.98%, and 53.12% in tensile strength, elastic modulus, failure strain, and absorbed failure energy at $85s^{-1}$ strain rate, respectively, compared to lowest strain rate ($0.0017s^{-1}$). Gilat et al. [9] investigated material (carbon/epoxy laminate) response under tensile test at different strain rate (range is 0.4×10^3–0.6×10^3) and evaluated for different adhesives and laminate combinations at different strain levels. The results showed a significant impact on the material behavior of the strain speed. It was observed from the experiment result that the tests with [45°] and [$\pm 45^{\circ}$] specimens have a more dominant impact on the peak stress of the strain frequency. Lim et al. [10] analyzed the influence on deformation mechanisms and tensile yielding of the loading speed (0.0001–0.1/s) and temperature (−45° to 70°) of polymer (nylon 6-based nanocomposites) also contain rubber particles (poly oligo ethylene glycol methacrylate). The volumetric strains result suggested that nanocomposites decreased the delamination of the organoclay layer and increased shear deformation. Elanchezhian et al. [11] investigated the mechanical behavior of GFRP and CFRP by experiment with the specimen at different strain frequencies and temperatures. CFRP's tensile and flexural strength is comparatively larger compared to GFRP, and it has the highest load amount of 36.262 KN and 1.785 KN, respectively. Velmurugan [12] examined the strain-dependent nature of glass/epoxy laminate filled with nano clay and found that when strain rates increases both strength and stiffness increases. Li et al. [13] examined the impact of strain speeds under tensile as well as compressive loads over warp-knitted and flat woven CFRP laminate. The result identified that tensile strength increased when the strain frequency has grown in both types of composite material though marginal influences are found on compressive strength. Fereshteh–Saniee et al. [14] examined the material properties of GFRP composite at the low level of strain. As a consequence, the strength and rigidity increased by 24.70% and 4.20% accordingly, increasing the frequency of the strain from 10^{-4} to $11 \times 10^{-2}s^{-1}$. Amijima et al. [15] determined the influence of strain speed on the compressive behavior of GFRP laminate. The strain speed ranged from 0.001 to $1.03 \times 10^2 s^{-1}$, and increased compressive strength with higher strain rate was observed.

In the present work, an attempt has been made to investigate the tensile nature of circular hole GFRP laminate at various loading rates. In all tests, specimens with the same geometry are used. The loading rate effect on open-hole tensile strength was examined with emphasis on damage mechanism and later compared with numerical results.

2 Materials, Process, and Fabrication

The glass fabric [600 GSM (Gram per square meter)] used in this experimental study is bidirectionally woven and is purchased from S. S. Polymer, Bengaluru. Thermosetting epoxy (Bisphenol-A) and hardener (Amine) were also procured from same manufacturer used in these experimental sets.

Firstly, the matrix is prepared by mixing the thermosetting resin and curing agent (10:1 ratio), followed by mechanical stirring for 5–7 min. Based on the stacking sequence, the glass woven fabric plies are rinsed using a soft paintbrush, and a heavy steel roller forced out the excessive resin [16]. Subsequently, laminate was secured in a resealable plastic carrier and compressed using a compression molding machine under the constant pressure of 19.8 MPa. Besides, laminate was kept at ambient temperature for 12 h under constant pressure for curing. According to the ASTM D5766 standard [17], the specimens (150 mm × 36 mm × 2.8 mm) were cut from the laminate. A drilling machine drilled the specimens for creation of 6 mm diameter hole at the center of the specimen (Fig. 1).

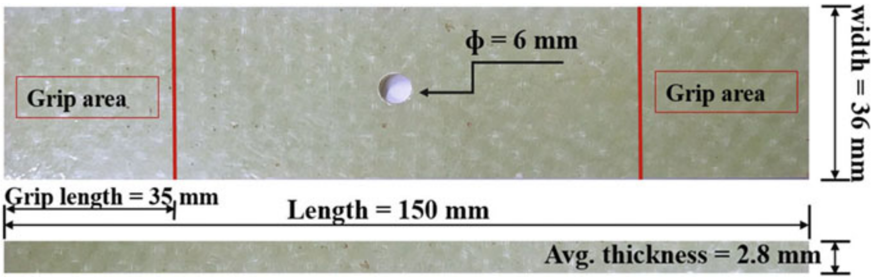


Fig. 1 Standard specimen dimensions

3 Experimental Setup

Testing was done on Hounsfield (H50KS), a computerized universal testing machine (UTM) with a peak load of 50 KN, as shown in Fig. 2. Tests were conducted at four separate loading speeds of 1 mm/min, 10 mm/min, 50 mm/min, and 100 mm/min. There were three specimens in each category of samples, and therefore, twelve specimens have been analyzed. The maximum tensile strength was determined from formula (1).

$$\sigma_{\max} = \frac{F_{\max}}{A} \tag{1}$$

where $F_{\max}$ is peak force sustained by experimental sample (N), A is gross cross-sectional area (excluding hole,mm^2), and $\sigma_{\max}$ is maximum tensile strength with an open hole (MPa).

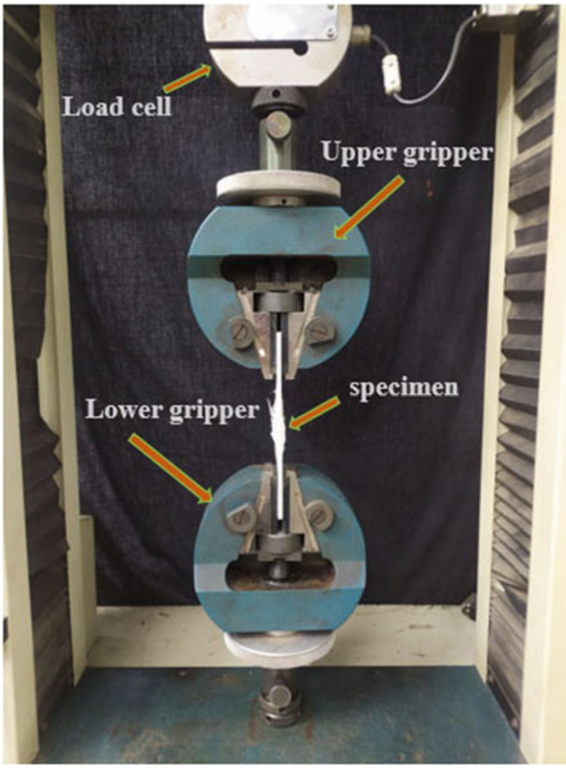
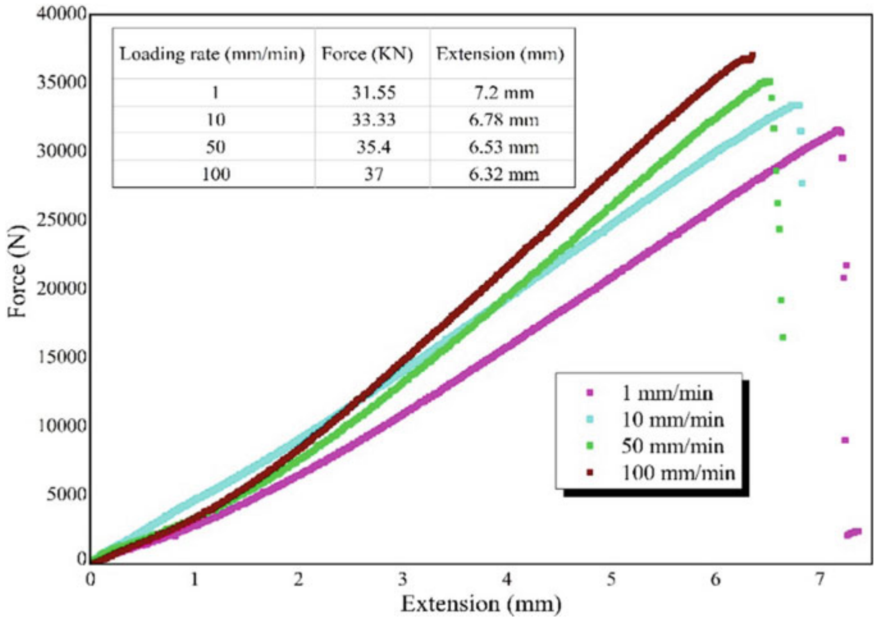


Fig. 2 Tensile testing experimental setup

4 Results and Discussion

The maximum load-carrying capacity of open-hole GFRP specimens increases, while deflection decreases when the loading rate is increased because of failing in a brittle way at a larger loading rate (Fig. 3). The load-carrying capacity increased by 5.6, 12.18, and 17.25% at loading rate of 10, 50, and 100 mm/min, respectively, compared with slower loading rate (1 mm/min), but deflection decreased by 5.83, 9.3, 12.22%.

Based on the results obtained from Eq. (1), the maximum tensile strength in composite specimens increased by increasing the loading rate, as shown in Fig. 4, due to non-homogeneous distortion in the sample and strain hardening after viscoelastic behavior of epoxy/hardener solution [18]. The ultimate tensile stress increased at a larger loading speed. The tensile strength increased by 7.02%, 8.72%, 15.04% at loading rate of 10, 50, and 100 mm/min, respectively. Lower the value of the CV in Table 1, so the result is precise in the experimental data from the same unit. Therefore, the result of specimens for a loading rate of 50 mm/min is more accurate as compared to other loading rates.



Loading rate (mm/min)	Force (KN)	Extension (mm)
1	31.55	7.2 mm
10	33.33	6.78 mm
50	35.4	6.53 mm
100	37	6.32 mm

Fig. 3 Force versus extension curves of tested specimens at different loading rates

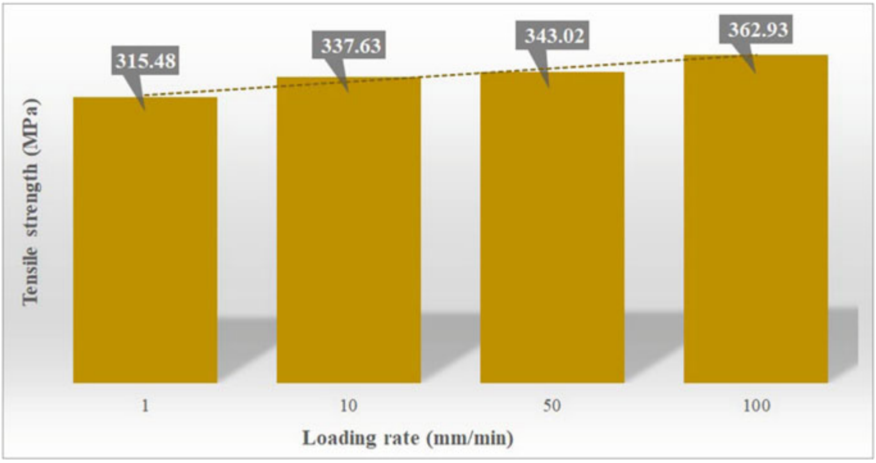


Fig. 4 Histogram of tensile strength at different loading rates

Table 1 Show precise results for each group specimen

Specimen group number	Loading rate (mm/min)	Tensile strength	
		SD	CV (%)
1	1	4.76	1.50
2	10	7.14	1.96
3	50	2.64	0.76
4	100	8.56	2.35

5 Fractographic Analysis

During the tensile test, the failure mechanism was observed through the digital microscope. The failure initiates with matrix cracking around the hole, whereas the crack surfaces around both upper and lower parts of the hole and exit to the edge side of the sample are shown in Fig. 5a.

Laminate fails at the hole in tension and displays several failure modes in various sub-laminates. The zero-degree plies failed laterally across the middle of the hole, and the angle plies failed through the lateral centerline of the hole in Fig. 5b.

Secondly, the delamination of ply, splitting of fiber, and fiber breakage have occurred simultaneously in the tensile test specimen, as shown in Fig. 6. However, the dominant mechanism of failure was observed to be splitting of fibers from the epoxy/hardener solution [19].

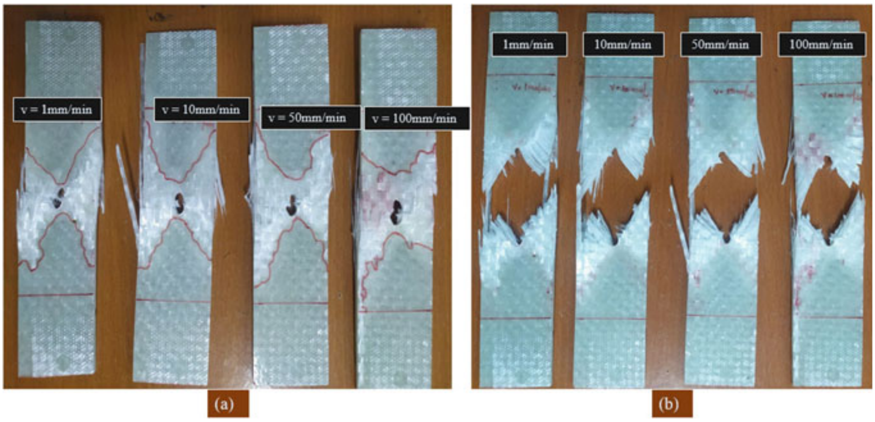


Fig. 5 Specimens after **a** failure, **b** fracture

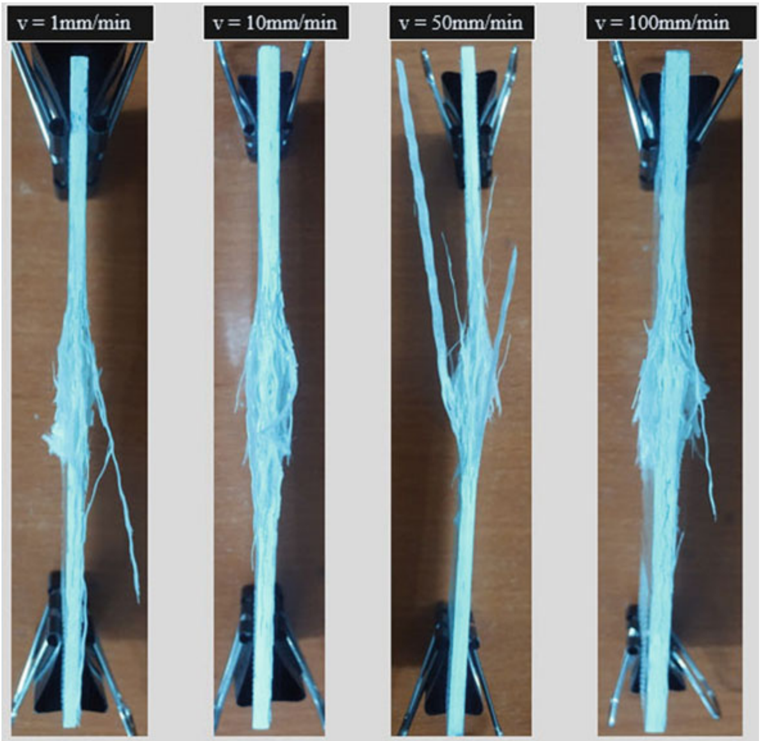


Fig. 6 Side view of samples after failure at different loading rates

6 Numerical Analysis

The numerical method is used to investigate the tensile failure pattern in the specimen at different time intervals during testing using Abaqus-6.14. The composite part with through-hole ($d = 6$) has been modeled as a deformable 3D shell. Nine engineering constants were defined for laminate, as shown in Table 2. Young modulus, shear modulus, and poison ratio of glass/epoxy lamina were chosen from Ref. [20]. GFRP laminate stacking sequence was created in the composite-layup option by taking each lamina thickness ($t = 0.35$ mm), material properties, and fiber angle. Create an instance in the assembly module and select dependent mesh. The step section specified analysis steps and forms of analysis. History output requests were also nominated in this module. Create constraint by coupling to hold the workpiece in the interaction module. The reference point (RP 2) was restricted as ENCASTRE in tension test simulation, while the reference point (RP 1) was moved by load. The meshed specimen is shown in Fig. 7.

The failure mechanism was observed from the simulation of the Abaqus model at different periods (52, 105, and 150 s) and loading rate (1, 10, 50, and 100 mm/min), as shown in Fig. 8. The area around the hole is more affected when the loading rate increases, and half of the hole is less moved than at a lower loading rate. The half portion of the hole is more shifted at a lower loading rate as it gives more time duration during testing and is at 45° sublamina in the laminate. During testing, the results in the failure mechanism are the same by both experimental and numerical methods,

Table 2 Engineering constants for simulation

Lamina	Physical properties (units of E and G = GPa)								
	E_{11}	E_{22}	E_{33}	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{13}	ν_{23}
Glass/epoxy	36.9	10		3.3		3.6	0.32		0.44

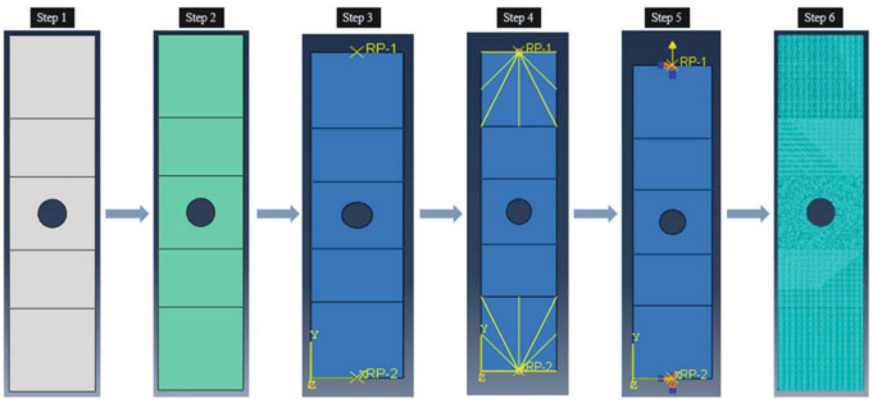


Fig.7 Process flow for preparing the model in Abaqus

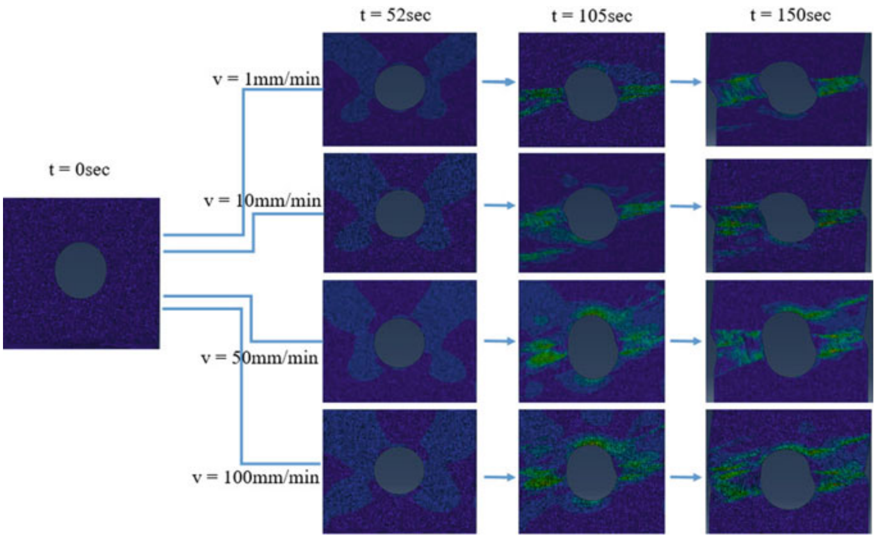


Fig. 8 Failure analysis through numerical simulation

as shown in Fig. 9. Thus, the simulation result is validated through a numerical approach.

7 Conclusion

The influence on maximum tensile strength and failure mechanisms of GFRP composites with an open hole of varying loading speed has been investigated. The work can be summarized as follows

- The load-carrying capacity of open-hole GFRP samples is increased, while the deflection decreases when the loading rate is increased. Compared with a slower loading rate (1 mm/min), the maximum load-carrying capacity increased by 17.25% at a loading rate of 100 mm/min, but maximum deflection decreased by 12.22% due to brittle fracture.
- As the loading rate increases, tensile strength increases. At the load speed of 100 mm/min, the maximum tensile strength increased by 15.04%.
- Fiber debonding is the highly dominant failure mechanism in open-hole tensile testing in comparison with matrix cracking, delamination, and fiber breakage.
- The area around the hole is more affected at a higher loading rate compared to a lower loading rate, and half portion of the hole moves more at the lowest loading rate.

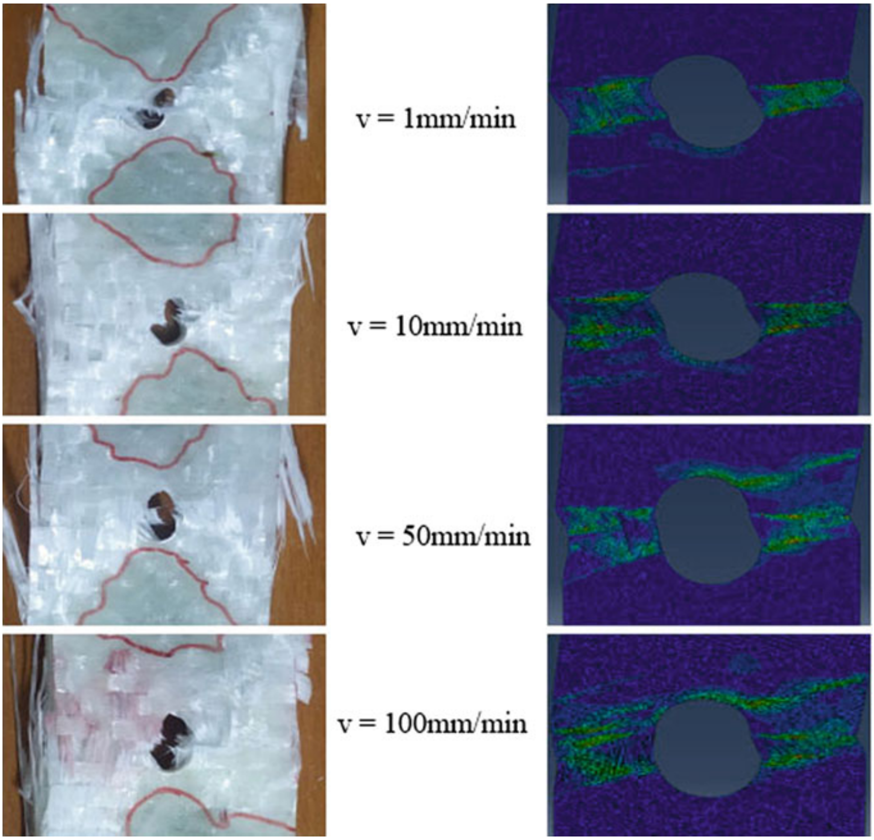


Fig. 9 Comparison between experimental and numerical approach through failure mechanism

- In the failure mechanism, the simulation outcomes had been in better covenant with the testing outcomes indicating the ability of the simulation methodology to estimate tensile failure behavior.

The experimental data reveal that rate-dependent constitutive relationships are helpful in modeling polymer composites and are used to estimate the effective failure response of composites. The information provided here is used to be useful for the creation of constitutive ideas.

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