DİKDÖRTGEN UHMWPE PLAKALARIN DİNAMİK PARAMETRELERİNİN MODAL ANALİZ İLE BELİRLENMESİ

MODAL ANALYSIS ON DETERMINATION OF DYNAMIC PARAMETERS OF RECTANGULAR UHMWPE PLATES

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ÖZET

Yarı kristal termoplastik olarak sınıflandırılan Ultra Yüksek Moleküler Ağırlıklı Polietilen (UHMWPE), yüksek özgül mukavemet, yüksek darbe direnci ve korozyona karşı yüksek direnç gibi birçok olağanüstü malzeme özelliği sunar; bu nedenle, UHMWPE'den yapılmış plakalar, otomotiv ve askeri gibi çok sayıda uygulama alanında yük taşıma bileşenleri olarak yaygın olarak kullanılmaktadır. Bu uygulamalarda, UHMWPE plakaları genellikle dinamik yüklere maruz kalır; bu nedenle, dinamik yükler altında gerçek çalışma koşullarını anlamak sağlam tasarım için çok önemlidir. Bu amaçla, delikli ve deliksiz UHMWPE dikdörtgen plakaların dinamik malzeme davranışı hakkında derinlemesine bilgi sağlayan ilk üç doğal frekans, karşılık gelen mod şekilleri ve sönüm oranları gibi çok önemli dinamik parametreler modal analizi ile belirlendi. Her iki dikdörtgen plakanın boyutları 150x100x4 mm iken, deliğin çapı 25 mm'dir. Ek olarak, modal analiz sırasında her iki plakaya bir tarafı sabitlenmiş sınır koşulları uygulandı. İlk üç doğal frekans ve karşılık gelen mod şekilleri, Abaqus yazılımında kullanılan Lancsoz özdeğer çözücüden her iki dikdörtgen plaka için çıkarıldı. Hem deneysel hem de sayısal sonuçlar, deliğin UHMWPE dikdörtgen plakada rijitlik azalmasına yol açtığını ve bunun da delik olmayan UHMWPE dikdörtgen plakanın doğal frekanslarına kıyasla daha düşük doğal frekanslarla yol açtığını ortaya koydu. Ayrıca, deliğin neden olduğu rijitlik azalması sonucunda, yarı güç bant genişliğine göre hesaplanan sönüm oranları, delikli dikdörtgen plaka için daha az bulundu. Bununla birlikte, yapısal şekil değişikliği (mod şekilleri) desenlerinin, kesme deliğinden etkilenmediği de ortaya çıktı. Deneysel sonuçlar, sayısal tahminlerle uyumluluğu karşılaştırıldı.

Anahtar Kelimeler: Ultra yüksek molekül ağırlıklı polietilen (UHMWPE), Modal Analiz, Doğal frekanslar, Sönüm oranları, Mod şekilleri

ABSTRACT

Ultra-High Molecular Weight Polyethylene (UHMWPE), classified as semi-crystalline thermoplastic, offers many outstanding material attributes such as high specific strength, high impact resistance and high resistance to corrosion; therefore, plates made of UHMWPE are widely used as load - carrying components in numerous application fields like automotive and military. In those applications, UHMWPE plates are generally subjected to dynamic loads; therefore, understanding their actual operating conditions under dynamic loads is crucial for robust design. To this end, very significant dynamic parameters, such as first three natural frequencies and corresponding mode shapes and damping ratios, that provide in-depth information regarding a dynamic material behavior were determined for UHMWPE rectangular plates with and without cut-out hole by conducting the modal analysis. While the dimensions of both rectangular plates are 150x100x4 mm, the diameter of the cut-out hole is 25 mm. Additionally, one side clamped boundary conditions were dictated to both plates during modal analysis. The first three natural frequencies and corresponding mode shapes were extracted for both rectangular plates from Lancsoz eigensolver utilized in Abaqus software. Both experimental and numerical results revealed that the cut-out hole leads to a stiffness reduction in the UHMWPE rectangular plate which results in lower natural frequencies compared to the natural frequencies of UHMWPE rectangular plate without cut-out hole. Furthermore, as a result of the stiffness reduction caused by the cut-out hole, damping ratios calculated based on the half-power bandwidth were found to be less for the rectangular plate with cut-out hole. Nevertheless, it was also revealed that the pattern of structural deflections (mode shapes) is not influenced by the cut-out hole. The experimental results were favorably compared to the numerical predictions.

Keywords: Ultra High Molecular Weight Polyethylene (UHMWPE), Modal analysis, Natural frequencies, Damping ratios, Mode shapes

1. INTRODUCTION

Plates manufactured from various types of polymers such as UHMWPE, ABS, PVC, PMMA are widely utilized as load carrying components in numerous engineering applications ranging from automotive to aerospace. Among them, UHMWPE classified as semicrystalline polymer is one of the most notable ones due to its many distinguished physical and mechanical properties including high impact resistance, high specific strength, high ductility, high wear resistance, high chemical resistance, and low density(Dangsheng, 2005; Kelly, 2002; Kurtz, 2015; Patel et al., 2020). In actual applications, UHMWPE plates are generally subjected to time-dependent dynamic loads which lead to excitations at different frequencies varying from low to high. Additionally, UHMWPE plates can experience damages resulting from the dictated dynamic loads. Thus, understanding their material behaviors under such these loads is vital for sound design. Dynamic parameters, including natural frequency, damping ratio and mode shape, directly provide in-depth information regarding the dynamic material behavior of structures(Sperling, 1990). Moreover, the damages taken place in structures can be found out by evaluating the mentioned dynamic parameters. Modal analysis acknowledged as the non-destructive evaluation method is extensively performed for the measurement of dynamic parameters. In reality, defects or damages resulted from the applied loads generally result in a reduction in stiffness, which causes a decrease in natural frequencies. Furthermore, this can lead to a change in dominant mode shapes. On account of this, defect and damages formed in structures are readily be detected by evaluating changes in natural frequencies and dominant mode shapes.

There have been many studies dedicated to theoretically determine both natural frequencies and mode shapes of plates. The free vibration analysis of isotropic plates possessing different boundary conditions has been well-documented by Leissa and Gorman(Gorman et al., 1982; Leissa, 1973). The methods proposed by these two researchers to the calculation of natural frequencies have been well-accepted to date, as well as providing very accurate results in comparison with exact outcomes attained from modal analysis. The effect of intentionally generated imperfections with various shapes including circular, square, and rectangular, on the natural frequencies of plates have been elucidated by many studies(Boay, 1996; Chikkol Venkateshappa et al., 2019; Liew et al., 2003; Mondal et al., 2015; Mundkur et al., 1994; Vinyas et al., 2021). Those studies have put forth that both mass and stiffness of the plates are reduced by the referred imperfections, and therefore the natural frequencies of plates alter.

Albeit the widespread use of UHMWPE plates in industrial applications, there has been no experimental study (modal analysis) found for the determination of its dynamic parameters after extensive literature survey. Thus, the study here aims at filling this deficiency in literature. To this end, the modal parameters of UHMWPE rectangular plates with and without cut-out circular hole have been determined by implementing modal analysis. The dimensions of the UHMWPE rectangular plate without cut-out hole are identical to the dimensions of plate with cut-out hole, and the dimensions of both plates are equal to 150x100x4 mm. It is worth noting that the diameter of the cut-out hole is equal to 25 mm. During modal analysis, the UHMWPE rectangular plates were clamped in one side. First three natural frequencies and corresponding mode shapes have been successfully acquired for both plates from modal analysis. Depending on the experimental modal analysis data, damping ratios have also been calculated for both plates following the half-power bandwidth method. To predict the first three natural frequencies and corresponding mode shapes, numerical analysis has been carried out in commercial finite element code ABAQUS. The predicted results have been compared to the experimental measurements in terms of first three natural frequencies and corresponding mede shapes. A very good agreement has been found between experiments and simulations.

2. MATERIALS AND METHOD

2.1. Material

Commercially sourced UHMWPE plate with the thickness of 4 mm has been purchased from company named ORBILAN. The exact brand name of the UHMWPE plate used in this study has been reported as PE 1000. Moreover, density and the molecular weight of the UHMWPE have provided as 930 kg/m^3 and 5x10^6 g/mol, respectively(Ercan, 2021). Two rectangular specimens with the dimensions of 150x100 mm have been cut from the large plate by using CNC router. Additionally, a circular hole with a diameter of 25 mm has been drilled in one of the UHMWPE rectangular plates at its geometric center. The rectangular plates with and without cut-out hole prepared for modal analysis are illustrated in Figure 1.

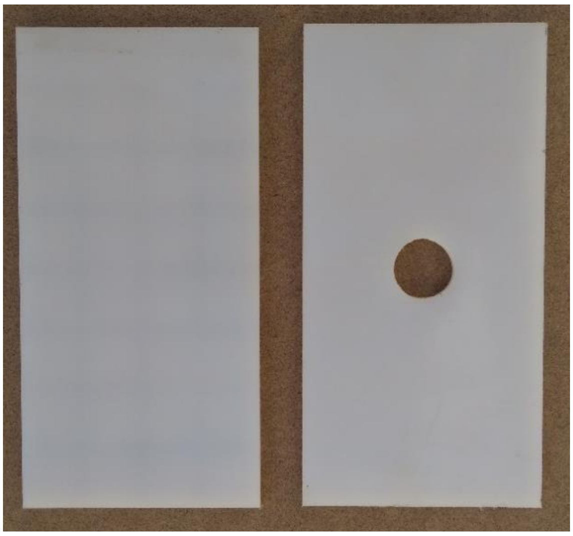

Figure 1: Rectangular UHMWPE specimens with and without cut-out hole.

2.2. Method

In order to obtain an accurate modal analysis data, a sufficient number of hammer hit points were specified on the rectangular specimens as depicted in Figure 2. The identical number of hit points was also described in Pulse LabShop software as illustrated in Figure 3.

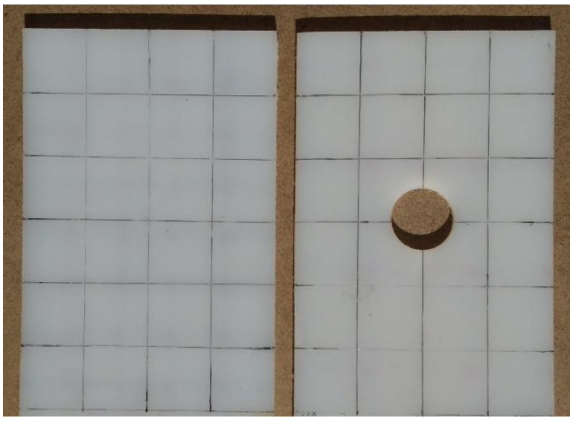

Figure 2: Hammer hit points defined on rectangular plates.

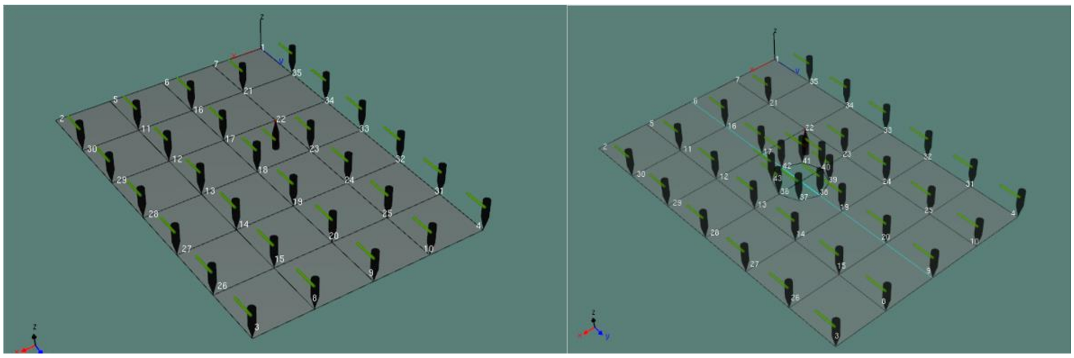

Figure 3: Hammer hit points and measurement sequence.

The experimental setup for the modal analysis is indicated in Figure 4. During the modal analysis, the acceleration data was acquired using the single axis accelerometer branded as Brüel&Kjaer 4513B. The accelerometer was mounted on the specimens with the help of honey, as shown in Figure 4. Additionally, Brüel&Kjaer 3050-B-060 type 6 channel data acquisition (DAQ) device was utilized with the Pulse LabShop 14.1 software in order to analyze the modal test data.

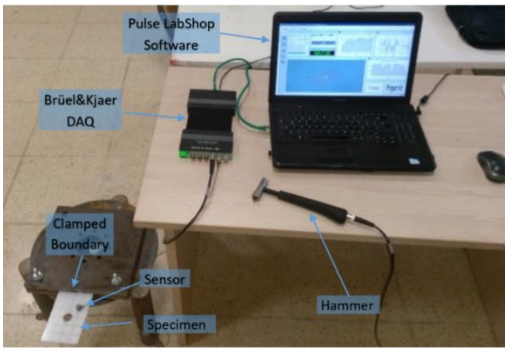

Figure 4: Experimental setup for modal analysis.

To attain an accurate acceleration data, each point shown in Figure 3 was first excited three times by the impact hammer, and then the average of accelerations generated by these three hits was taken as actual test data. After measuring the acceleration data, the modal parameters of UHMWPE rectangular plates, including first three resonant frequencies and corresponding mode shapes were determined based on frequency response function (FRF) data that is internally generated by software. Furthermore, damping ratios were calculated by applying half-power bandwidth method to FRF data(Olmos et al., 2010; Papagiannopoulos et al., 2011; Thomson, 2018; Wang, 2011). Figure 5 indicates how to calculate the damping ratios in detail by means of the half-power bandwidth method.

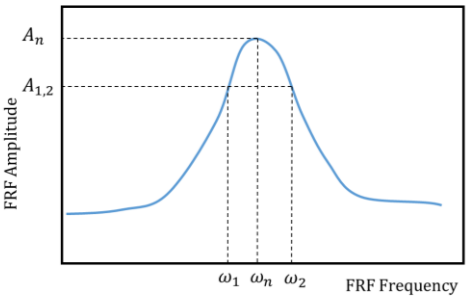

Figure 5: Half-Power bandwidth method for the calculation of damping ratio.

The expression for the calculation of damping ratio (ζ) can be given as follows:

$$\zeta = \frac{\omega_2 - \omega_1}{2\omega_n} \tag{1}$$

Where ω_n is the natural frequency corresponding the peak amplitude A_n. Furthermore, ω_1 and ω_2 are the frequencies corresponding the amplitudes A_1 and A_2, respectively. It is a fact that A_1 and A_2 are equal to each other, and both can be computed with the following expression.

$$A_{1,2} = \frac{A_n}{\sqrt{2}} \tag{2}$$

By using the aforementioned formulations, the damping ratios for UHMWPE rectangular plates were calculated and reported in the present study.

3. FINITE ELEMENT ANALYSIS

In order to predict the first three natural frequencies and corresponding mode shapes, finite element analysis on the UHMWPE rectangular plates was implemented in Abaqus engineering software. The finite element models of rectangular specimens with and without cut-out hole are illustrated in Figure 6. The grid geometries of specimens were meshed in Hypermesh pre-processor that is a powerful tool to handle the mesh of specimens with complex shapes. The problem here was considered as 3D, and therefore reduced integration shell element formulation (S4R) with enhanced hourglass control was used. This element type (S4R) is the commonly used shell element formulation in numerical analysis since it provides accurate results with less computational time (Khalili et al., 2011; Paulo et al., 2013). As it can be comprehended from Figure 6, the clamped boundary conditions were imposed to the one side of the rectangular specimens.

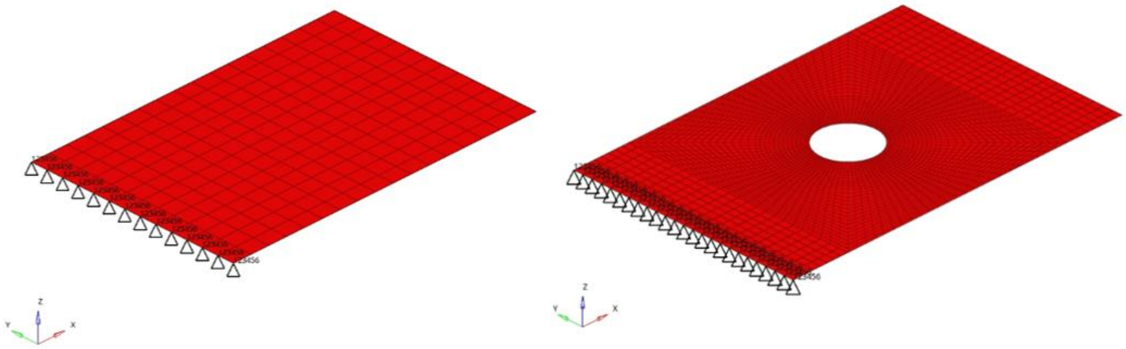

Figure 6: Finite element models of uhmwpe rectangular plates with and without cut-out hole.

Natural frequencies and corresponding mode shapes were obtained using the Lancsoz eigensolver in Abaqus that is a very effective eigensolver for the extraction of modal parameters like natural frequencies and mode shapes(Nouby M, 2009; Yang et al., 2013).

Such material properties including elastic modulus, Poisson's ratio, and density, are the parameters considered in vibration analysis; therefore, the referred parameter values for the same brand of UHMWPE have been found in the literature as given in Table 1.

Table 1: The parameters used in the numerical simulations for vibration analysis of UHMWPE(Ercan, 2021).

Elastic Modulus (MPa)	Poisson's Ratio	Density (tonne/mm^3)
1500	0.46	930e-12

4. RESULTS

FRF results obtained from the modal analysis of UHMWPE rectangular plates with and without cut-out hole are shown in Figure 7. Additionally, the first three natural frequencies measured from the modal analysis for both rectangular plates are tabulated in Table 2.

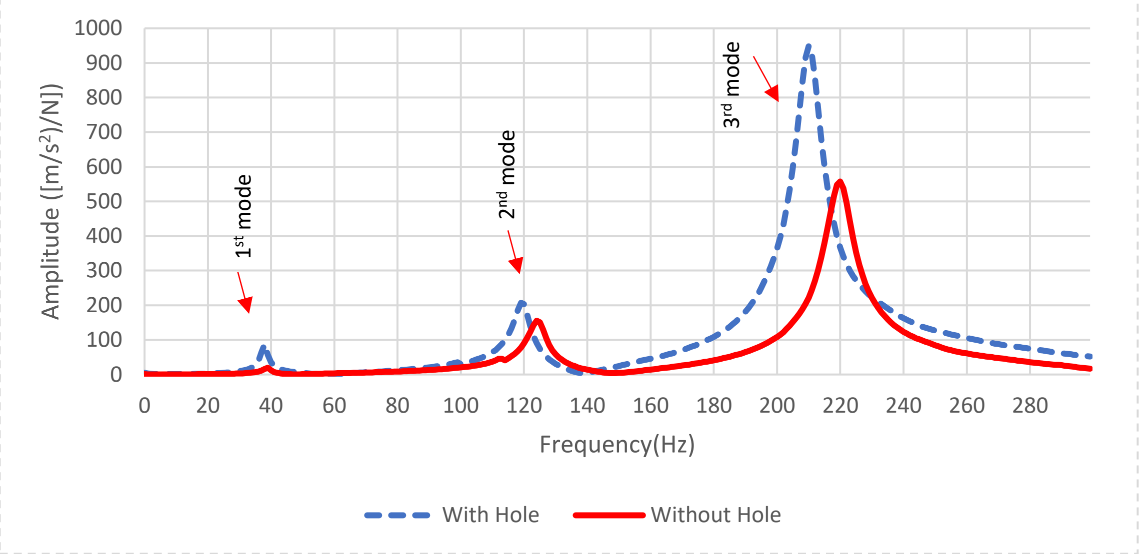

Figure 7: FRF obtained from the modal analysis of UHMWPE rectangular plates with and without cut-out hole.

Table 2: Natural frequencies of UHMWPE rectangular plates (with and without cut-out hole).

Mode	**Frequency (Hz)**	
	Without hole	With cut-out hole
1	39	38
2	124	120
3	220	210

As it can be acknowledged from both Figure 7 and Table 2, the first three natural frequencies of rectangular plate without cut-out hole are always higher than the natural frequencies of rectangular plate with cut-out hole. This implies that the cut-out hole leads to a reduction in the stiffness of plate which results in lower natural frequencies. As seen in Table 2, differences between natural frequencies become more distinguishable at higher frequencies.

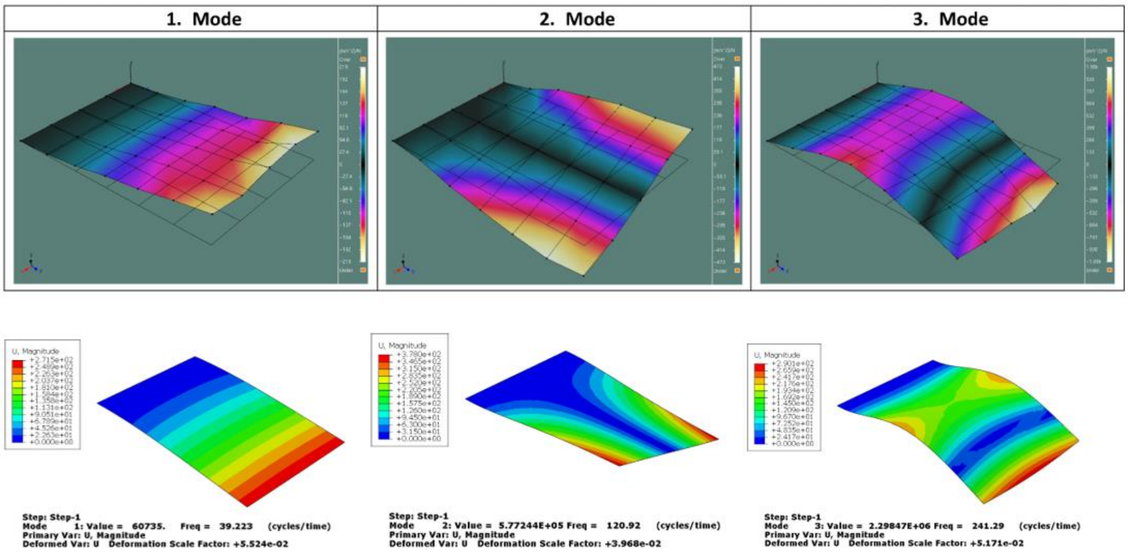

Figure 8: Comparison of experimental first three mode shapes with numerical predictions for rectangular UHMWPE plate without cut-out hole.

The first three mode shapes attained from the modal analysis are favorably compared to the predicted mode shapes for the plate without cut-out hole as depicted in Figure 8. In terms of mode shapes, the numerical predictions are in good agreements with the measurements. Whereas 1st and 3rd mode shapes are known as the bending modes, 2nd mode shape is the twisting mode. In the same manner, experimental mode shapes are compared to the predicted mode shapes for the plate with cut-out hole as illustrated in Figure 9.

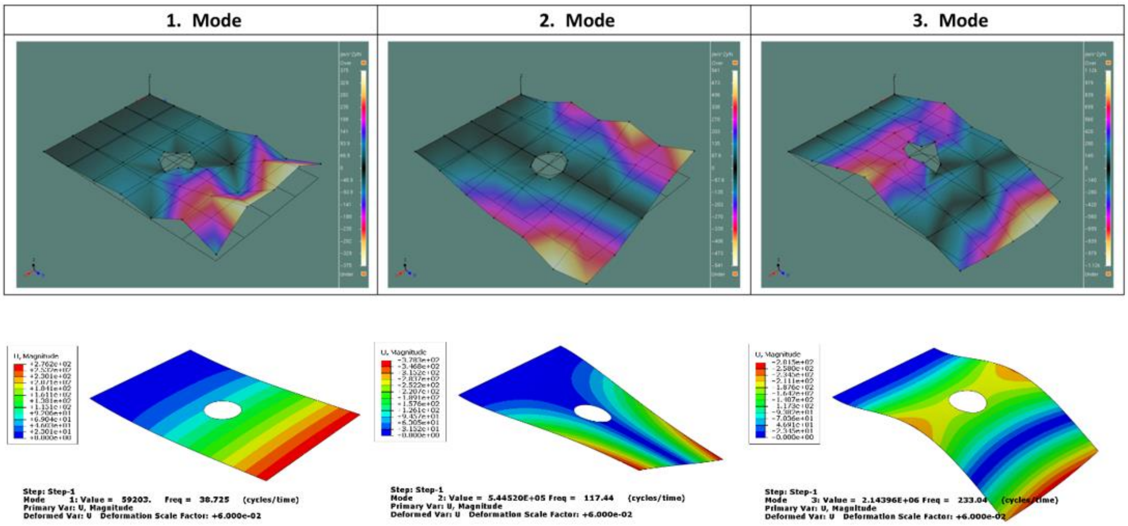

Figure 9: Comparison of experimental first three mode shapes with numerical predictions for rectangular UHMWPE plate with cut-out hole.

From both experimental and numerical mode shapes, it can be concluded that the cut-out hole does not affect the mode shapes, but natural frequencies are influenced.

Table 3. Comparison of experimental natural frequencies with numerical predictions.

Mode	**Frequency (Hz)**					
	Without hole			With cut-out hole		
	Exp	FEA	Error (%)	Exp	FEA	Error (%)
1	39	39.223	0.57	38	38.725	1.91
2	124	120.92	2.48	120	117.44	2.13
3	220	241.29	9.68	210	233.04	10.97

Table 3 provides the comparison of experimentally determined natural frequencies with the numerical predictions. From Table 3, it can readily be stated that the first three natural frequencies of UHMWPE rectangular plates with and without cut-out hole have been accurately predicted by finite element analysis. The maximum error ratio found between experiments and simulations is 10.97%. Accordingly, the error ratio between measurements and predictions increases with the increase of natural frequency. This can be explained by the fact that the material behavior of UHMWPE is highly strain rate dependent, implying that its elastic modulus increases with increasing strain rate. Moreover, UHMWPE exhibits dissimilar material behavior under tension and compression. In other words, compressive modulus of UHMWPE is not identical to its tensile modulus. Nevertheless, UHMWPE here has been considered as an isotropic material and the constant modulus obtained from tension tests has been used in our simulations. Additionally, dissimilar material behavior between tension and compression has not been accounted for.

Damping ratios calculated for rectangular plates with and without cut-out hole are reported in Table 4. The damping ratio decreases with increasing natural frequency in both rectangular plates. Nevertheless, the damping ratio of rectangular plate without cut-out hole is always higher than the damping ratio of plate with cut-out hole for each natural frequency.

Table 4. Damping ratios of UHMWPE plates in first three natural frequency.

Mode	**Without cut-out hole**	**With cut-out hole**
1	0.0291	0.0265
2	0.0222	0.0214
3	0.0208	0.0183

5. CONCLUDING REMARKS

Depending on both experimental measurements and numerical predictions, the following conclusions can be drawn:

The cut-out hole causes a reduction in the stiffness of rectangular plate, which leads to lower natural frequencies compared to the rectangular plate without cut-out hole whereas the mode shapes are not influenced by the cut-out hole.

Both the first three natural frequencies and corresponding mode shapes are well-predicted by the numerical analysis. Nevertheless, increasing error ratio between measurements and predictions with increasing natural frequency is mainly due to the used isotropic material model in our simulations. Actually, UHMWPE is not isotropic, and its material behavior is highly dependent on strain rate and hydrostatic pressure as well as its extrusion direction. In order to predict more accurate results for higher frequencies, more complex and advanced material models should be utilized in numerical simulations.

The effect of cut-out hole on the natural frequencies become more distinguishable at higher frequencies.

The damping ratio is found to decrease with increasing natural frequency for both UHMWPE rectangular plates. Moreover, the damping ratio computed for the rectangular plate without cut-out hole is always larger than the damping ratio of rectangular plate with cut-out hole for each natural frequency. Depending on this, it can be underlined that the cut-out hole impairs the structural integrity of the plate, which leads to a decrease in the energy absorbing capacity.

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