Proceedings of the 10th World Congress on Mechanical, Chemical, and Material Engineering (MCM'24)
Barcelona, Spain - August 22-24, 2024
Paper No. ICMIE 106
DOI: 10.11159/icmie24.106

Optimization of Flex Spline Component of Harmonic Gear Drive Using Prepreg Composites

S.A. Dizaji[1], Beril Arıkan[2]
[1,2]TED University
Ziya Gökalp Cd. 48/A, 06420 Çankaya, Ankara, Türkiye
sehram.dizeci@tedu.edu.tr; beril.arikan@tedu.edu.tr

Abstract **-** The harmonic drive gear offers superior precision and repeatability, outshining traditional gearing. This study aims to minimize stress and weight in the Flex Spline (FS) component while simultaneously enhancing torque capacity through the application of an anisotropic composite material. Initially, steel analysis was conducted for validation, using reference data to confirm the numerical model generated with the implicit ABAQUS solver. Subsequently, the hybrid FS design was introduced, employing a combination of carbon fiber and glass fiber composite materials bonded with adhesive resin. Analytical comparisons were made between these materials, and variations in adhesive bonding thickness were assessed for their impact on stress values. Consequently, the hybrid FS resulted in a 27.7% increase in working torque capacity and 38.5% in weight reduction.

Keywords**:** Harmonic drive, Flex spline, Composite, Optimization

1. Introduction

Harmonic drive mechanisms excel in industrial applications due to their efficient use of materials, high torsional rigidity, and minimal kinematic faults compared to other mechanical drives. They stand out from traditional gearing by offering exceptional positioning precision, surpassing typical gear precision by more than 30 arc seconds, and achieving repeatability within +3 to -3 arc seconds, thanks to their simplified components and multiple tooth engagement. Moreover, they operate without backlash, handling extreme torque capacities despite being smaller and lighter than their traditional counterparts. With nearly linear stiffness and low interior friction, harmonic drives maintain high efficiency, typically exceeding 80% at nominal input speed and torque [1].

Compared to conventional gears, harmonic drive mechanisms exhibit unparalleled precision, achieving better repeatability and positioning accuracy. Their design, characterized by simplified components and multiple tooth engagement, allows for minimal dependency on gear precision or tooth pitch inaccuracies, ensuring extremely low hysteresis losses. Operating without backlash, these drives maintain high torque capacities while demonstrating exceptional stiffness and efficiency, often surpassing 80% efficiency at nominal input conditions, highlighting their minimal internal friction and superior performance [2].

The Harmonic Drive gear consists of three main parts: the Circular Spline (CS), a durable stationary ring; the Flex Spline (FS), a flexible yet torsional stiff component crucial for producing vibrations; and the WG (WG), an efficient torque converter with a cam-like interior profile for transmitting torque to the Flex Spline.

Numerous researchers have concentrated on analyzing the stress within the Flex Spline's teeth structure to optimize their shape and achieve maximum fatigue life [3-4]. Their work demonstrated that employing Finite Element Analysis (FEA) for the harmonic drive FS provides more accurate predictions of maximum stress compared to experimental methods. Additionally, studies focusing on mathematical models for both the WG, and the FS aim to enhance the overall performance of harmonic drives. For instance, Chen, Yi-Cheng, et al. [5] aimed to utilize two-dimensional (2-D) finite element analysis (FEA) to characterize a qualified harmonic drive featuring an involute FS profile. Initially, they developed a mathematical model of the FS with an involute tooth structure using a straight-edge rack cutter and principles from gearing theory. Sohoo et al. [6] measured strains at various points on the FS wall surface in a split cam WG harmonic drive. They found significantly higher maximum von Mises stress compared to a traditional cam setup which shows that the stress capacity has increased.

Xu et al. [7] investigated the load distribution on the FS in a harmonic drive with various types of WG cams. Their study explored the impact of thin-walled FS constructions on deformation energy dispersion. Huang et al. [8] opted for a circumferential modification tooth structure profile instead of a radial one to maintain transmission accuracy and extend the service life of the harmonic drive. Trang et al. [9] developed a stress calculation methodology for the FS using finite elements and mechanical analyses. They identified the highest stress concentration at the tooth structure's root, offering valuable insights for designing and optimizing the flex spline, especially in assessing reliability and promptly evaluating stress during the design phase.

Jeong et al. [10] showcased that the composite FS surpassed its one-part steel counterpart, exhibiting superior radial flexibility and exceptional damping capacity at crucial frequencies, while also reducing the component's mass. Similarly, Jeon, Han Su, and Se Hoon Oh [11] observed comparable outcomes in their analysis of stress and vibration properties in the WG. Their examination involved two models: one using a steel FS and the other a hybrid model comprising steel and composite materials. Folega P. and G. Siwiec [12] investigated the impact of steel and steel-composite materials on FS strength using finite element methods. Their study revealed that reinforcing the FS with carbon-fiber or glass-fiber strengthened epoxy resin led to reduced stress, correlating with increased vibration frequencies. Additionally, Folega P. [13] emphasized the importance of flex spline's vibration attributes and flexibility. A comparison between steel-composite and steel flex splines showed advantages in weight reduction, higher inherent frequencies, and decreased torsional angles in composite structures. Despite manufacturing challenges, employing hybrid flex splines strengthened with composite materials was recommended due to their enhanced properties.

The study aims to minimize the overall mass of the FS and enhance its torque capability. Utilizing finite element analysis, a harmonic drive sample proposed by Chen, Yi-Cheng, et al. [5] is reconstructed through numerical models. Stress simulations during the validation stage ensure the accuracy of the verification process. The flex spline's cup is manufactured with carbon fiber and glass fiber epoxy composite materials, while the teeth are made of steel and bonded together using adhesive. The finite element method is then employed to optimize the design, reducing stresses, and improving the torque transmission ratio.

2. Material Properties

The steel material used for both the steel FS and the steel teeth in the hybrid composite FS is detailed in Table 1.

Table 1. AISI 4340 / DIN 34CrNiMo6 steel alloy [5]

E (GPa)	Poisson's Ratio	Yield Strength (MPa)	UTS (MPa)	Fatigue stress (MPa)	Density (g/cm3)
200	0.29	860	1282	640	7.8

Table 2 demonstrates the glass fiber mechanical properties which was reported by Sun, X. S., et al. [14].

Table 2. properties for Glass Fiber Composite [14]

E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	υ_{12}	υ_{13}	υ_{23}	G_{12}(MPa)	G_{13}(MPa)	G_{23}(MPa)
48700	16800	16800	0.28	0.28	0.4	5830	5830	6000

Table 3 exhibits the carbon fiber properties obtained by Yahya, N. A., and Safa Hashim [15] and were used in this work as material properties for numerical model.

Table 3. properties for Carbon Fiber Composite [15]

E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	υ_{12}	υ_{13}	υ_{23}	G_{12}(MPa)	G_{13}(MPa)	G_{23}(MPa)
48700	16800	16800	0.28	0.28	0.4	5830	5830	6000

Table 4 depicts the properties for epoxy resin utilized to bond the prepreg composite materials to the steel flexspline in the numerical model.

Table 1. different epoxy resin properties [15]

Adhesive type	E (MPa)	G_I (MPa)	G_{II} (MPa)
Epoxy resin Araldite LY3505/XB3405	3500	1296	1296
Epoxy resin Araldite 2015	1800	662	662

3. Numerical analyses

Abaqus/Standard Solver defaults to automatic incrementation but selecting the right time increment relies on observing convergence rates. A few iterations might warrant larger increments, while slow convergence suggests smaller ones. The utilized CZM model represents a connection between traction (T) and separation (δ) on an interface, as outlined in [17]. The characterization of the traction-separation mechanism is determined by either the element type or material model. In investigating structural components, the CZM method often employs shapes like bilinear, exponential, and trapezoidal.

CS and WG components are designed as two-dimensional discrete rigid wires. A 2-node 2-D linear rigid link (R2D2) element type was chosen for both components in plane strain. The analysis employed the 4-node bilinear plain strain quadrilateral with reduced integration (CPE4R) for the FS as well.

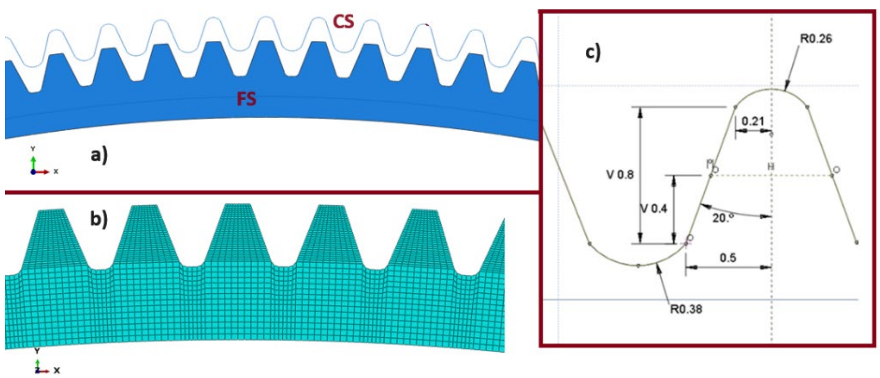

Fig. 1: The numerical model for steel FS in ABAQUS; a) Assembly of FS and CS, b) The dimensions for CS teeth, and c) Mesh pattern in FS component

For the hybrid harmonic drive, the inner Flex Spline contained 0.5 mm thick carbon fiber material bonded to a 0.1 mm adhesive layer connected to a steel section encompassing the remaining regions, including the teeth. Due to varying mechanical behavior in composites, material orientation was considered crucial to ensure load-bearing alignment. Specifically, the Flex Spline was expected to handle loads aligned with its maximum load direction. Delamination, a critical concern in the hybrid Harmonic Drive design, was addressed by employing cohesive zone modeling (CZM). The region was designated using a 4-node two-dimensional cohesive element (COH2D4), as shown in Fig. 2.

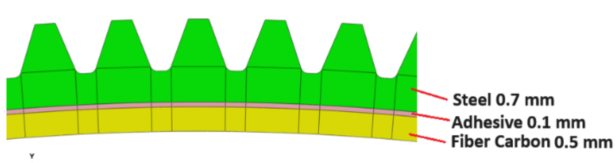

Fig. 2: The numerical model for hybrid FS

4. Results and Discussions

Based on the assessment for steel flex spline, the reference work [5] found peak stress of 577 MPa in the fillet and 614 MPa in the contact region under a 50 Nm torque. Meanwhile, this study identified a maximum fillet stress of MPa and a contact stress of 617 MPa as shown in Fig. 3. The mesh sensitivity analyses have been done to find the best size which reflects the experimental results. Despite slight variations between analyses and the sample work, finite model proves enough reliability.

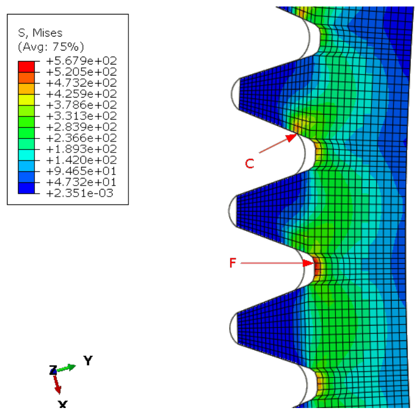

Fig. 3: The stress values in the fillet area of steel FS

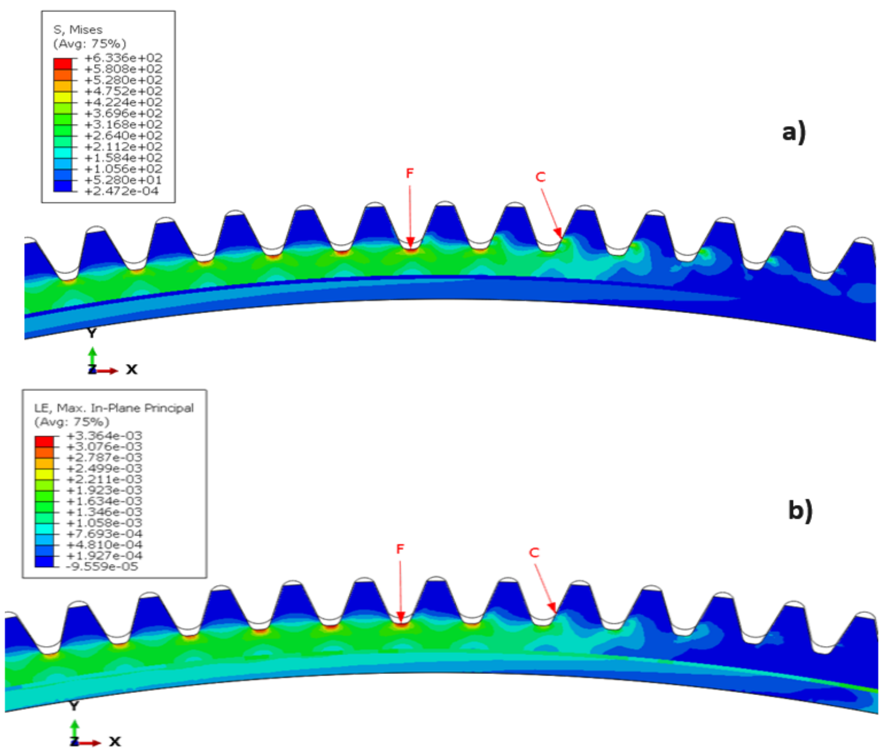

Fig. 4: FEM analyses results for hybrid design with carbon fiber as composite; a) stress analysis, b) strain analysis

Fig. 4a displays the maximum von Mises stress in a hybrid harmonic drive. Contrary to the steel FS, where the stress peak is in the contact region, the hybrid model exhibits a peak of 633 MPa in the fillet region. Fig. 4b presents the strain values in the hybrid FS, coinciding with the area of maximum stress, reaching a value of 0.00336. Although this hybrid design significantly reduces the weight of the FS by employing composite material for nearly half the rim thickness instead of steel, it also raises both von Mises stress and strain values compared to the steel FS. However, the increase in stress and strain values is 11% and 8%, respectively, both of which are considered negligible. This is because the yield stress of the steel section, where the maximum stress occurs (Table 1), is 860 MPa, ensuring elastic deformation in the fillet region of the hybrid design. Fig. 4a indicates notably low stresses within the composite section of the hybrid design, ensuring a promising aspect: the likelihood of delamination in the composite region is highly unlikely.

Fig. 5a illustrates the stresses within the new hybrid FS subjected to a 50 Nm torque, with the glass fiber allocated to the composite region. The analysis reveals a concerning finding: the fillet region experiences a maximum stress of 641 MPa, surpassing the fatigue strength reported as 640 MPa. Moreover, the maximum strain value (Fig. 5b) for the glass fiber FS is noted as 0.003843. Comparatively, it's evident that glass fiber imposes higher stress values than carbon fiber.

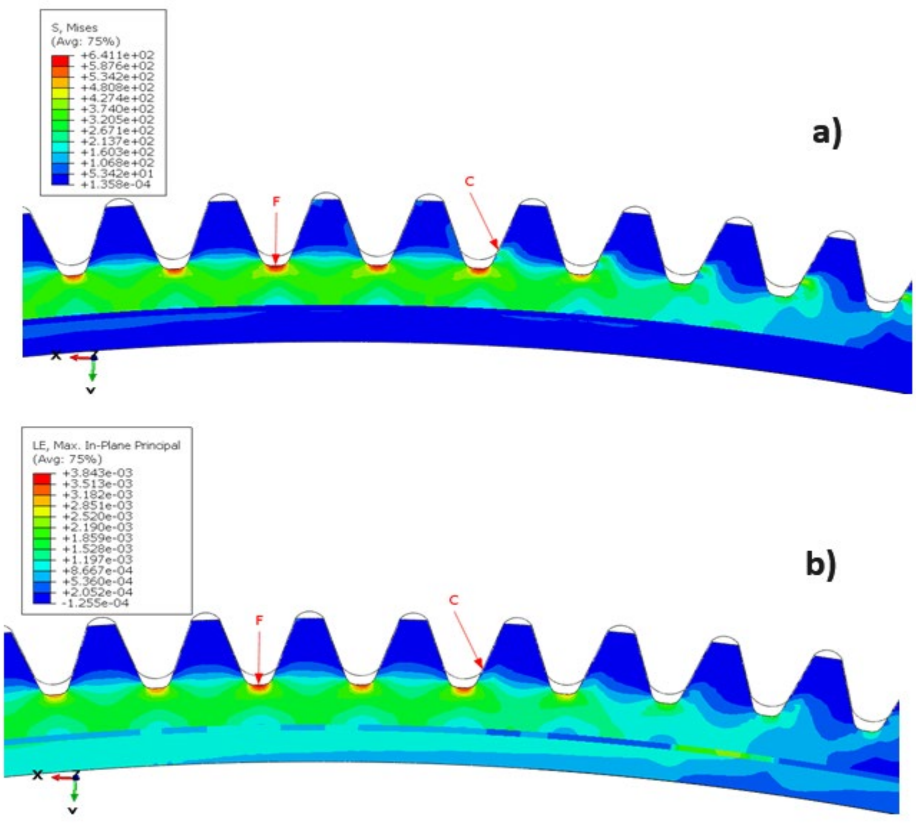

Fig. 5: FEM analyses results for hybrid design with glass fiber as composite; a) stress analysis, b) strain analysis

To investigate delamination or adhesive failure, a Quads damage model with a fracture displacement of 0.1 mm was utilized. However, no damage occurred within the layer as a result of the applied loadings.

The epoxy resin Araldite LY3505/XB3405, was replaced with the epoxy adhesive Araldite 2015. Despite the huge difference between these two adhesives (Table 4), no considerable alterations were detected in the stresses within the FS upon analyzing the results. The maximum stress observed in the FS remained at 637 MPa and it appears that the adhesive material change has negligible impact on both torque capacity and weight.

Fig. 6 presents stress values for hybrid harmonic drive models under a 50 Nm torque, achieved by reducing the thickness of the Flex Spline's composite region by 0.1 mm while increasing the steel region. Notably, the von Mises stresses visibly decreased with this adjustment. This improvement has steered the hybrid FS models away from the fatigue strength limit, enabling a gradual increase in the applicable torque for these designs. As it is evident the thickness of the composite section can not be more than 0.5 mm because the fatigue stress can be surpassed, and failure will occur. It was found that the reduction in weight relative to the steel FS depends on the composite thickness employed. At best design with 0.5 mm of composite thickness, the weight of the rim thickness section can be reduced by as much as 38.35 percent in the optimized hybrid FS. This weight reduction is very important in the values of natural frequency of the FS leading to the vibrational errors in the final positioning application.

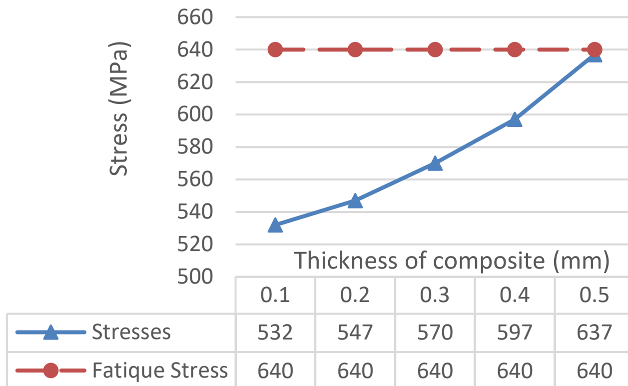

Fig. 5: FEM analyses results for hybrid design with glass fiber as composite; a) stress analysis, b) strain analysis

4. Conclusion

The study aimed to contrast a steel flex spline (FS), as more critical part in harmonic drive gear, with a composite alternative, aiming to highlight the benefits of the composite harmonic drive gear. Multiple composites and epoxy adhesives were examined to explore various parameters. Experimentation involved testing different composite thicknesses to determine the maximum applicable thickness aligned with the fatigue life criterion established for the steel material.

- Utilizing a hybrid FS results in a lighter component, reducing the natural frequency and vibrational impact. Stress values in the fillet area of both the hybrid and steel FS show minimal difference, indicating the favorable nature of the hybrid design.
- lower thickness of the composite section in the hybrid FS results in lower stresses in the fillet region. However, utilizing the maximum allowable thickness, which was found to be 0.5 mm, is essential to effectively use the lighter FS.
- The use of different adhesives has minor effects on the efficiency of the FS.
- Replacing carbon fiber with glass fiber results in higher stresses in the fillet section of the steel material, exceeding the material's fatigue limit.

Acknowledgements

The authors are willing to thank Dr. Omer Music for his kind support of the study.

References

[1] Tuttle, T. Douglas, “Understanding and modeling the behavior of a harmonic drive gear transmission” Diss. Massachusetts Institute of Technology, 1992.

[2] Nye, W. Ted, P. K. Robert "Harmonic drive gear error: Characterization and compensation for precision pointing and tracking." JPL, The 25th Aerospace Mechanisms Symposium. 1991.

[3] O. Kayabasi, and F. Erzincanli. "Shape optimization of tooth profile of a flex spline for a harmonic drive by finite element modelling." Materials & design 28.2 2007: 441-447.

[4] W. Ostapski, "Analysis of the stress state in the harmonic drive generator-flex spline system in relation to selected structural parameters and manufacturing deviations." Bulletin of the Polish Academy of Sciences: Technical Sciences, 2010, 683-698.

[5] Chen, Y. Cheng, "Study of a harmonic drive with involute profile flex spline by two-dimensional finite element analysis." Engineering Computations, 2017.

[6] V. Sahoo, M. S. Bhabani, and M. Rathindranath. "Stresses in flex gear of a novel harmonic drive with and without pay load." Australian Journal of Mechanical Engineering 20.4, 2022, 1054-1068.

[7] Xu, Zhaoxiang, W. Yazhen and W. Haifeng. "Calculation and Analysis of Deformation Characteristic and Energy Dissipation of Flexible Bearings in Harmonic Drive for Industrial Robots." Journal of Physics: Conference Series. Vol. 2365. No. 1. IOP Publishing, 2022.

[8] J. Huang, J. Xu, N. Qian, S. Wei, "Circumferential spatial tooth profile modification of flex spline for harmonic drive: A novel method and a case study." 2022.

[9] Trang, T. Trung, "A quick stress calculation method for flex spline in harmonic actuators based on the finite element method." Cogent Engineering 9.1, 2022.

[10] Jeong, S. Kwang, and S. Hoon Oh. "Development of the composite flex spline for a cycloid-type harmonic drive using net shape manufacturing method." Composite Structures 32.1-4, 1995, 557-565.

[11] Jeon, H. Su, and S. H. Oh. "A study on stress and vibration analysis of a steel and hybrid flex spline for harmonic drive." Composite Structures 47.1-4, 1999, 827-833.

[12] P. Folęga, and G. Siwiec. "Numerical analysis of selected materials for flex splines." Archives of metallurgy and materials 57, 2012, 185-191.

[13] P. Folęga, "Study of dynamic properties of composite and steel-composite flex splines of harmonic drives." Journal of Vibroengineering 17.1, 2015, 155-163.

[14] X. S. Sun, "A multi-axial fatigue model for fiber-reinforced composite laminates based on Puck’s criterion." Journal of Composite Materials 46.4, 2012, 449-469.

[15] N. A. Yahya, and S. Hashim. "Stress analysis of steel/carbon composite double lap shear joints under tensile loading." Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 230.1, 2016, 88-104.

[16] M. Smith, “ABAQUS/Standard User's Manual”, Version 6.9. Dassault Systèmes Simulia Corp, 2009.

[17] Salve, K. Ajinkya and N. J. Sudhindra. "Implementation of cohesive zone in ABAQUS to investigate fracture problems." Proceedings of the National Conference for Engineering Postgraduates RIT, NConPG, 15. 2015.