NUMERICAL INVESTIGATION OF THE STRENGTH OF STIRRUP MADE OF KEVLAR

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Abstract. In this study, the mechanical behavior of stirrups commonly used in reinforced concrete structures when manufactured from Kevlar instead of steel was investigated using numerical analysis. Kevlar, an aramid fiber with advantages such as light weight, high tensile strength, flexibility, and corrosion resistance, is attracting attention as an alternative reinforcement element to steel, particularly in humid and aggressive environmental conditions. However, Kevlar's anisotropic structure causes its elastic modulus and shear stiffness to vary significantly depending on direction, significantly affecting its deformation behavior under loading. In this context, steel and Kevlar stirrups were modeled under the same geometric conditions, and their deformation and stress distributions under axial load were compared. The analysis results showed that Kevlar stirrups tend to deform more in their weaker directions, while steel, due to its isotropic structure, provides a more balanced stress distribution. Furthermore, since the study did not include a concrete model, it is anticipated that the high deformations that could limit Kevlar's performance in real-world applications will be significantly reduced when evaluated in conjunction with concrete. The findings suggest that Kevlar stirrups have potential for use in structural systems with appropriate engineering design, but that evaluation with more comprehensive models that include concrete-stirrup interactions is necessary.
Key words: Kevlar stirrup, alternative reinforcement, anisotropic behavior, finite element analysis, deformation behavior, structural performance

Аннотация. В данном исследовании методом численного анализа изучалось механическое поведение хомутов, обычно применяемых в железобетонных конструкциях, при их изготовлении из кевлара вместо стали. Кевлар - арамидное волокно, обладающее такими преимуществами, как малый вес, высокая прочность на растяжение, гибкость и коррозионная стойкость, - привлекает внимание в качестве альтернативы стальной арматуре, особенно во влажной и агрессивной среде. мационное поведение под нагрузкой. В рамках исследования были смоделированы стальные и кевларовые хомуты в одинаковых геометрических условиях, после чего было проведено сравнение их дефорОднако анизотропная структура кевлара приводит к тому, что его модуль упругости и жёсткость на сдвиг сильно различаются в зависимости от направления, что оказывает существенное влияние на его деформаций и распределения напряжений при осевой нагрузке. Результаты анализа показали, что кевларовые хомуты склонны в большей степени деформироваться в своих слабых направлениях, в то время как сталь, благодаря своей изотропной структуре, обеспечивает более равномерное распределение напряжений. Кроме того, поскольку исследование не включало модель бетона, предполагается, что высокие деформации, которые могут ограничивать эффективность кевлара в реальных условиях, будут значительно меньше при рассмотрении его совместной работы с бетоном. Полученные данные свидетельствуют о том, что кевларовые хомуты потенциально могут применяться в строительных конструкциях при надлежащем инженерном проектировании, однако необходима их оценка с использованием более комплексных моделей, учитывающих взаимодействие бетона и хомута.
Ключевые слова: кевларовый хомут, альтернативное армирование, анизотропное поведение, метод конечных элементов, деформационное поведение, несущая способность

Introduction

Stirrups, used in the construction industry, are critical for reinforced concrete structures. A stirrup is a binding element, usually made of steel bars, that increases the durability of a structure by resisting tensile stresses in concrete. While durable, concrete can fracture under tension or compression. This is where the stirrup comes in, strengthening the structure by increasing the concrete's load-bearing capacity. By being incorporated into the concrete, the stirrups ensure the bond between the steel and the concrete, thus

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increasing the structure's durability, especially against dynamic loads such as earthquakes. While steel is generally used in traditional stirrup production, alternative materials have become increasingly popular in recent years. Kevlar, a material made from aramid fibers, boasts superior properties such as high tensile strength, light weight, flexibility, and corrosion resistance. Kevlar's corrosion resistance is a significant advantage, especially for structures in humid areas and near the sea, as it eliminates the risk of steel stirrups rusting over time and weakening the structure's strength. However, it's important to note that Kevlar stirrups have different mechanical properties than steel. Although Kevlar is lighter than steel and has a higher modulus of elasticity, its lower elongation capacity can limit its load-bearing capacity in some cases. Therefore, the use of Kevlar stirrups in reinforced concrete structures should be carefully designed according to engineering calculations and the needs of the structure. Although not as stiff as steel, Kevlar stirrups can significantly increase structural strength with proper design and application. He et al. [1] investigated the shear behavior of concrete beams strengthened with GFRP-steel hybrid stirrups. The mechanical behavior of stirrup-supported enhanced welded concrete-filled L-shaped steel tubular billet columns under axial compression was investigated by Wang et al. [2]. Yuan et al. [3] determined the mechanical behavior of recycled aggregate-filled steel tubular columns with square spiral stirrups under compression. The bearing load capacities of UHPC (Ultra-High-Performance Concrete)-coated CFST (Core Concrete-Filled Steel Tube) columns under axial compression were investigated by Xie et al. [4]. Yang et al. [5] investigated the behavior of high-strength concrete-filled columns surrounded by high-strength spiral stirrups under axial compression. Liu et al. [6] determined the axial compression performance of a steel-reinforced concrete column with high-strength multiple spiral stirrups. The behavior of GFRP-reinforced columns with composite spiral stirrups under concentric compression was investigated by Zhang et al. [7]. Asan [8] performed the modal analysis of the column frame made of carbon/glass fiber composite. In another study, he investigated the ballistic behavior of UHMWPE and Kevlar plates [9]. In this article, the deformation and stress states of Kevlar stirrups under axial loads were investigated and compared with conventional steel stirrups.

Materials and Method

In this numerical study, the test elements were designed, the dimensions of which are shown in Figure 1. Kevlar and steel were used as stirrup materials. The mechanical properties of the materials used are given in Table 1.

table-1

Mechanical properties of materials [10,11]

Material	E_x*(MPa)*	E_y*(MPa)*	v_{xy}	v_{yz}	G_{xy}*(MPa)*	G_{yz}*(MPa)*	*Density (kg/m³)*
Kevlar	*80000*	*5500*	*0.34*	*0.4*	*2200*	*1800*	*1380*
Structural Steel	*200000*	*-*	*0.3*	*-*	*-*	*-*	*7850*

In Table 1, E_x,E_y represent the elasticity modules in the x and y directions; v_{xy} represents the Poisson ratio for the $x-y$ plane; v_{yz} represents the Poisson ratio for the $y-z$ plane;; G_{xy} represents the shear module in the $x-y$ plane; G_{yz} represents the shear module in the $y-z$ plane. The finite element model of the designed test element, the boundary conditions applied to the model, and the number of elements and nodes of this model are given in Table 2.

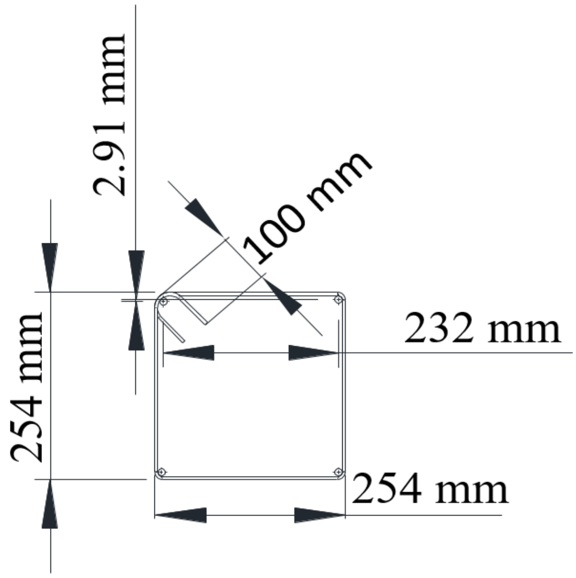
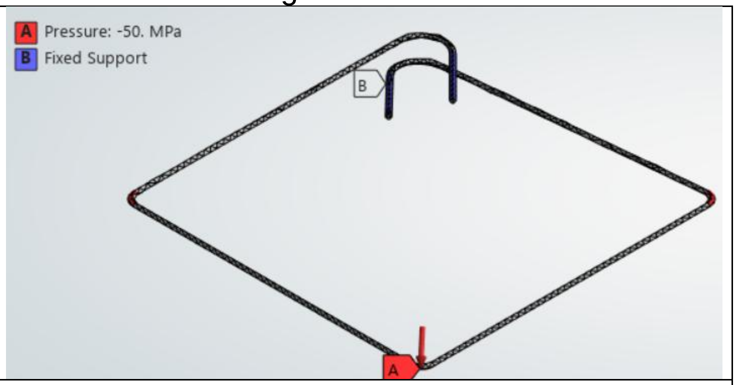


Fig.1 Dimensions of designed test elements [8]

Table 2.

Finite element models of the designed test element, boundary conditions applied to the models, number of elements, and number of nodes belongs to these models

Finite Element Model and Boundary Conditions A Fixed Support B Tensile Stress	
Number of Elements	1801
Number of Nodes	921

Results and Discussion

The data obtained as a result of the study are presented in Table 3. According to these results, it was seen that the use of Kevlar and steel as stirrup materials resulted in quite different mechanical behaviors. Since Kevlar is a structurally anisotropic material, its modulus of elasticity and shear stiffness vary significantly with directions. Low stiffness, especially in weak directions, caused more deformation under loading and explained the high deformation levels observed in the analysis. In contrast, steel, with its isotropic and high stiffness properties, limited both deformation and stress generation more stably. In steel stirrups, due to its higher stiffness and uniform mechanical property distribution, stress was distributed more evenly. Although Kevlar being much lighter than steel provides an advantage, this lightness does not alone improve structural performance due to the lower stiffness of the material. These findings are consistent with the behavior generally observed in the literature when FRP (Fiber Reinforced Polymer) stirruped reinforcement is used in reinforced concrete beams. For example; It has been reported that crack control is more limited in FRP-reinforced beams compared to steel beams[12], and that crack width

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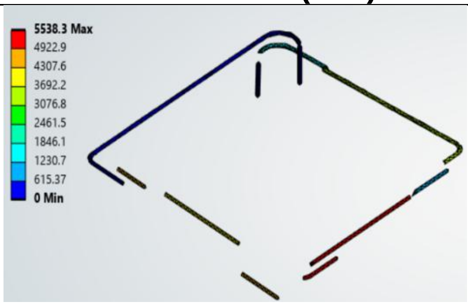
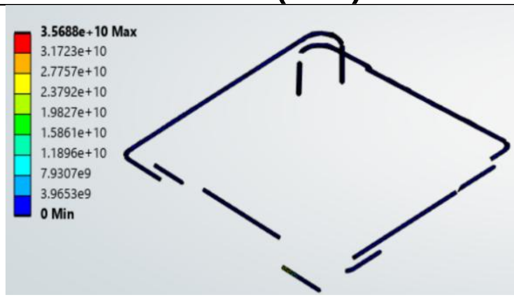
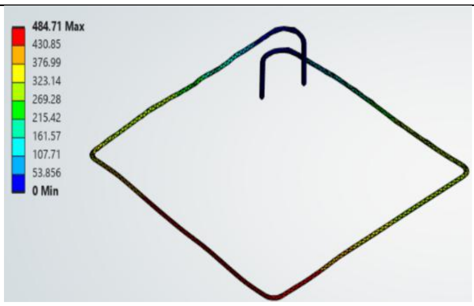
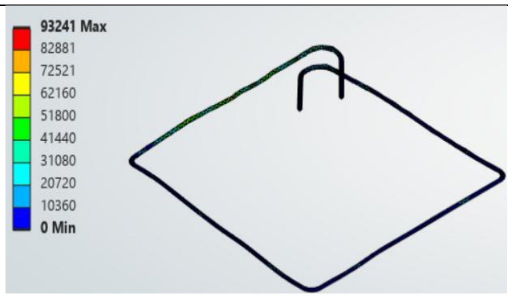
and deformation are also greater than in steel beams[13]. As reported in the literature, adding concrete to the model can significantly limit deformation, especially in more flexible materials like Kevlar, make the stress distribution more realistic, and more accurately reflect the material's actual operational performance. Therefore, the current findings represent the behavior of Kevlar alone and are not an exact representation of the actual situation in practice.

table 3.

Deformation and stress results of specimens

Material	Deformation(mm)	Stress(MPa)
Kevlar		
Steel		

Conclusion

This study compared the behavior of Kevlar and steel stirrups under axial load to reveal the structural properties of the two materials. The results showed that while Kevlar offers significant advantages such as light weight and corrosion resistance, its anisotropic structure causes higher deformations without the addition of concrete. Steel, with its isotropic and more rigid structure, distributed stress more evenly and limited strain. The exclusion of concrete from the model increased the observed deformations, particularly in the Kevlar stirrups, and therefore, the obtained findings represent the independent behavior of the material. Therefore, more comprehensive analyses that include concrete-stirrup interactions are needed to evaluate the performance of Kevlar in real-world reinforced concrete systems. Future studies will more accurately demonstrate the potential of Kevlar stirrups in practical applications.

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