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RESEARCH ARTICLE

Urban Furniture Design Using Steel Fibre Reinforced Concrete with Digital Design

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ABSTRACT

This research, conducted on the use of steel fibre reinforced concrete (SFRC) in urban furniture, investigates the performance of this material, which has the potential to offer more durable and aesthetic solutions than traditional concrete. In this study, both experimental and numerical methods were used to evaluate the mechanical properties of the SFRC and its applicability in urban furniture. As a result of the experiments conducted on concrete mixtures containing different ratios of steel fibres, it was observed that the ratio of steel fibres significantly affected the mechanical properties of concrete, such as compressive strength, flexural strength, and fracture energy. The obtained data show that steel fibres increase the strength of concrete and reduce the risk of cracking, thereby enabling the production of more durable structures. In addition, the stress distribution and crack formation in the concrete internal structure were examined using computer-aided analysis. In this way, we better understood how steel fibres affect the behaviour of concrete, and important data were obtained for the design of urban furniture with different geometries. As a result, this study shows that the use of steel fibre reinforced concrete in urban furniture offers many advantages. SFRC provides both aesthetically rich options and structurally more durable solutions. In this way, urban furniture should be both visually attractive and long-lasting.

Keywords: Steel fibre reinforced concrete, Urban furniture, Materials science, Grasshopper, Karamba3D

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1. Introduction

In the 21st century, with the rapid development of urbanisation processes, cities have become not only areas where housing and infrastructure services are provided but also spaces that are constantly evolving in terms of aesthetics and functionality. This process requires cities to offer liveable spaces that appeal to users not only functionally but also aesthetically. Urban furniture is an important component of cities in this context. Used in parks, squares, roads, and other public areas, urban furniture must meet both aesthetic and functional expectations. The materials used in urban furniture design play a critical role in meeting these expectations. Although traditional concrete has been widely used in the construction sector for many years, it is insufficient for structures with thin sections and complex forms. Cracks, durability problems, and aesthetic limitations are some of the weaknesses of traditional concrete. These shortcomings have led to a search for more durable, flexible, and aesthetic solutions. In recent years, various new materials and technologies have been developed as a result of these searches. One such material is steel fibre reinforced concrete (SFRC). SFRC stands out because of its high strength and durability. Exhibiting superior mechanical properties compared to traditional concrete, this material is particularly prominent for its crack resistance, energy absorption capacity, and long-lasting structure (Gupta et al., 2023). The advantages of SFRC make it attractive, especially for use in urban furniture with thin and complex geometries. Research on the use of this material in urban furniture can offer new solutions that comply with fundamental design principles such as aesthetics and functionality. Urban furniture is an element that increases human interaction in the city, provides user comfort, and at the same time strengthens the city's identity aesthetically. While the widespread use of concrete offers a cost-effective solution in the production of urban furniture, it has certain limitations, especially in terms of aesthetics and durability (Nilimaa et al., 2023). In this context, SFRC symbolises the beginning of a new era in urban furniture. By offering both aesthetic variety and durability, this material goes beyond the traditional usage limits of concrete and supports innovative approaches to urban furniture design. Although traditional concrete is a widely used material in the construction sector, there is a need for new materials due to cracking and durability problems, especially in thin-section structures. SFRC is an innovative material developed to increase crack resistance and improve the mechanical performance of concrete. SFRC provides extra strength

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to concrete as a result of the homogeneous distribution of steel fibres within the concrete, and thus minimises the risk of cracking (Liew & Akbar, 2020). This characteristic renders SFRC an attractive material, especially in areas such as thin sections, complex geometric structures, and urban furniture with aesthetic concerns. The advantages of SFRC are not limited to increasing crack resistance but also go beyond the limitations of traditional concrete in terms of aesthetics (Singh, 2017). This material can make an aesthetic contribution to urban furniture with different colours, textures, and surface applications. At the same time, the SFRC, which offers significant advantages in terms of sustainability, emerges as a cost-effective solution because of its longer lifespan and reduced maintenance requirements. There have been many studies in the literature on steel fibre reinforced concrete. Studies on the use of SFRC in structural elements, in particular, have examined in detail the high strength and crack resistance of this material. Ossama et al. (2021) presented important findings on the use of this material in structural elements such as beams and slabs by examining the mechanical performance of SFRCs with different fibre types and ratios (Osama, ve diğerleri, 2021). Anbuchezian et al. (2023) experimentally evaluated the effect of different additives on the crack resistance of SFRC (Anbuchezian et al., 2023). In another study by Hosseinzadeh et al. (2023), the energy absorption capacity of SFRC was studied, and the performance of this material under harsh environmental conditions was detailed (Hosseinzadeh et al., 2023). However, the literature on the use of SFRCs in more specific and aesthetically oriented applications, such as urban furniture. Blazy et al. (2022) made a significant contribution in this area by evaluating the use of glass fibre reinforced concretes in smart cities (Blazy et al., 2022). Graur et al. (2023) investigated the effect of geometric forms on the aesthetic and functional designs of concrete furniture (Graur et al., 2023). Studies by Soulioti et al. (2015) and Ghosni et al. (2016) have shown how steel fibres improve the mechanical properties of concrete, revealing the potential of SFRC for use in urban furniture (Soulioti et al., 2011), (Ghosni et al., 2016). However, existing studies in the literature have generally focused on structural elements, and comprehensive studies detailing the applications of SFRC in urban furniture are rare. This situation increases the importance of this study, which aims to investigate the potential of SFRC in applications in which aesthetic and functional requirements are at the forefront, such as urban furniture. The main question of this research is whether steel fibre reinforced concrete can perform better than traditional concrete in urban furniture and whether this material can offer more durable and aesthetic solutions. The hypothesis of this research is as follows:

- Digital simulations can accurately predict the behaviour of SFRCs in different geometries and optimise design processes.

The main purpose of this study is to investigate the potential use of SFRC in urban furniture and to fill the gap in the literature on this topic. The aesthetic and mechanical advantages of the SFRC are evaluated both theoretically and experimentally. In addition, the behaviour of the SFRC in different geometries will be simulated using digital design tools, and the results of these simulations will be verified using physical tests. In this way, this study aims to obtain important findings on how SFRC can be used in the design and production processes of urban furniture. The use of SFRC in urban furniture can offer new solutions that meet the aesthetic and functional requirements of modern cities. The importance of this study stems from the fact that SFRC can be evaluated as a material that can contribute to the aesthetics and durability of urban furniture. Given the existing deficiencies in the literature, this study can be an important source of information on the use of SFRC in urban furniture. The structure of the study is organised as follows: In the first section, the research method related to the use of SFRC in urban furniture is explained. In the second section, the theoretical foundations of the SFRC are discussed by focusing on its mechanical properties and aesthetic advantages. Numerical analyses and simulations conducted using digital design tools are presented. The test results of the SFRC samples and their analyses are included. The fourth section contains the discussion section. In the last section, an evaluation of the findings obtained throughout the study is presented, and recommendations for the future are presented. In conclusion, this research investigates the potential use of steel fibre reinforced concrete in urban furniture both theoretically and experimentally. In thin and complex geometries where traditional concrete is weak, the high strength, flexibility, and aesthetic advantages of SFRC offer new possibilities for urban furniture design. This study examines in detail how SFRC can be integrated into architectural design processes, how it can be modelled with digital tools, and how it can meet both the aesthetic and functional requirements of urban furniture. The findings will contribute to the durable and aesthetic design of urban furniture and offer innovative solutions that will improve the quality of urban spaces.

2. Methodology

2.1. Research Model

A mixed-methods research model was used in this study. The mixed-methods approach combines quantitative and qualitative research methods and complements each other. Within the scope of the study, quantitative data were obtained through physical and digital testing of the mechanical properties of steel fibre reinforced concrete, while qualitative data were obtained from the literature to form a theoretical framework. This method aims to comprehensively analyse the performance of SFRC in urban furniture.

2.2. Research Design

Quantitative data were obtained from experimental studies conducted on SFRC mixtures with different material ratios and from analyses conducted in Rhino, Grasshopper, and Karamba3D. Through these experiments, numerical data on the mechanical properties of SFRC (strength, flexibility, etc.) were collected. Qualitative data were obtained by reviewing existing scientific publications. In this way, information about the use of the SFRC in previous studies and the results obtained was obtained. By evaluating both quantitative and qualitative data together, the advantages, disadvantages, and potential application areas of using SFRC in urban furniture were clarified. This approach provides a deeper and more comprehensive understanding of the use of SFRC in urban furniture.

2.3. Study Group and Universe

In this study, urban furniture prototypes were produced using steel fibre concrete mixtures with different material ratios were examined. The focus of this research is on small-scale structural elements used in urban areas such as city squares and parks; in other words, urban furniture. The experiments conducted on these prototypes provide important data on the structural and aesthetic performance of using steel fibre concrete in such structural elements.

2.4. Data Analysis

All data collected in the study was analysed carefully. Numerical data obtained from experimental studies were examined in detail to reveal the mechanical properties of concrete. In this way, a clearer understanding of important parameters such as the strength and flexibility of concrete was obtained. The data obtained from the computer simulations were visualised using graphs and tables, allowing for a better understanding of the behaviour of concrete in different regions. In this way, important details such as the stress distribution and crack formation in the concrete internal structure can be obtained. Finally, all the data obtained from both the experimental and computer-aided methods were combined, and a comprehensive evaluation was made of the use of steel fibre reinforced concrete in urban furniture. Thanks to this evaluation, the advantages, disadvantages, and usage limits of concrete in such applications were determined, and an important roadmap was created for future studies.

2.5. Reliability and Validity

The reliability and validity of the research were ensured through various methods, increasing the objectivity and generalizability of the results. Experimental studies were carried out using standard methods and measurement tools and were repeated on several samples with different steel fibre ratios. It can be concluded that the results obtained are generally valid. In addition, the material models used in the digital simulations were verified by comparing them with the real experimental results. This also increased the reliability of the simulations. Throughout this process, a systematic approach was adopted to minimise subjective effects.

3. Results

In this study, the mechanical behaviour and structural performance of steel fibre reinforced concrete were investigated using experimental and numerical methods. Concrete mixtures containing different ratios of steel fibres were prepared, and the important mechanical properties, such as compressive strength, flexural strength, and fracture energy, of these mixtures were determined. In addition, experimental studies were conducted on the prepared specimens, and the obtained data were supported by FEA. The obtained findings provide important design parameters for the use of SFRC in structural elements.

3.1. Mechanical Test Results

A comprehensive experimental study was carried out to improve the mechanical properties of reinforced steel concrete, which is gaining increasing importance in the construction sector. In this study, 14 different concrete mixtures with different material ratios were prepared. Important mechanical properties, such as compressive strength, flexural strength, and fracture energy, were evaluated on specimens obtained from the prepared mixtures. Because of the tests conducted on the specimens under standard conditions, the effects of the steel fibre ratio on the strength and other mechanical properties of concrete were investigated. In this way, it is aimed to contribute to the construction of safer and more durable urban furniture by determining the most suitable usage ratios of concrete with different material ratios.

Table 1. Concrete Components Table.

Mixture No.	Cement	Silica Sand (0.5 mm)	Silica Sand (0.52 mm))	Silica Fume	Mosaic Semolina (24 mm) Basalt Black	Steel wire tip 2 (3D30 mm)	PP Fibre (12 mm)	PP Fibre (30 mm)	Glass Fibre (12 mm)	Additive hyperplasticizer	Water
N0	200	279	397	0	0	0	0	0	0	23	170
N1	200	154	151	96	0	35	3	0	0	91	200
N2	200	147	143	96	0	35	0	0	15	91	200
N3	200	147	143	96	0	35	0	0	10	109	200
N4	200	144	0	65	73	35	0	0	10	82	150
N5	200	173	170	74	0	35	0	0	10	91	190
N6	200	146	143	87	0	0	15	0	10	109	200
N7	200	173	170	87	0	0	0	0	0	91	150
N8	200	154	151	87	0	0	0	0	5	91	200
N9	200	154	151	87	0	0	0	10	5	91	170
N10	200	162	159	87	0	0	3	10	0	91	165
N11	200	146	125	65	94	35	3	0	0	26	180
N12	200	146	132	65	94	0	3	10	0	26	200
N13	200	135	121	65	94	35	3	0	0	26	200

Table 1, which lists the components of concrete mixtures mixed in different proportions, was prepared to produce concretes with different properties. In this way, it is aimed to determine the most suitable concrete mixture for a specific application by comparing the performances of different concrete mixtures. Such studies are important to understand how the properties of concrete, such as its strength, permeability, and workability, respond to different component ratios.

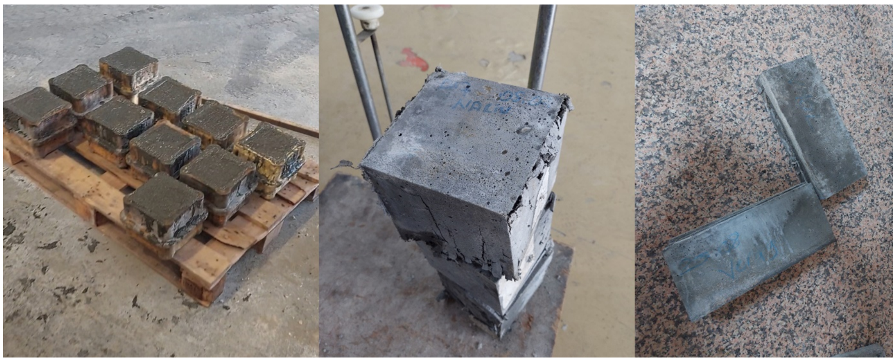


Figure 1. Concrete Mix Development Process.

The sample shown in Figure 1 was developed based on the information obtained from the test results of the previous sample. Thus, new samples with better performance were produced by eliminating the deficiencies and inadequacies observed in the previous samples. In particular, the aim was to obtain a concrete mixture with fluidity suitable for easy shaping in moulds for thin-section concrete urban furniture while also meeting the desired strength values. In this process, each sample was optimised according to the test results of the previous one, gradually approaching the concrete mixture most suitable for the desired properties.

Table 2. Properties of fresh and hardened concrete mixtures.

Mixture No.	Mixer Speed (rpm)	Depression (mm)	Decomposition	Other Observations
N0	11	No	No	Normal Consistency
N1	11.4	No	No	Very Fluent
N2	11.6	No	No	Less Fluent
N3	10	Yes	Decomposition	Very Strict
N4	11.5	No	No	Good Consistency
N5	12	Yes	Aggregate Settlement	Very Fluent Decomposition
N6	11	No	No	Very lightweight fluid
N7	11	Yes	No	Precipitation
N8	11	No	No	Good Consistency
N9	11	Yes	No	Good Consistency
N10	12	No	No	Very Fluent
N11	12	No	No	Less Sticky
N12	11	No	No	Thick Consistency
N13	11	No	No	Low Movement

The first table gives a detailed overview of the properties of the fresh concrete mixtures. In the evaluation of these properties, parameters such as mixer revolution, slump, and segregation (Table 2) were used. The mixer revolution is a factor that directly affects the homogeneity of the concrete mixture, while the slump and segregation parameters provide important information about the workability of the concrete and the homogeneity of the mixture. The segregation values indicated as "Yes" and "No" indicate whether undesirable segregation occurred in the concrete mixture. The rest of this section includes more subjective evaluations, such as the consistency of the concrete. The second table presents the mechanical properties of the samples after hardening, including their compressive strength, flexural strength, fracture energy, and peak load. By combining these two tables, the effects of different mixture parameters on the properties of concrete in both fresh and hardened states can be examined. Thus, concrete mixtures with the desired properties can be designed.

Table 3. Concrete mix performance evaluation table.

Mixture No.	Compressive Strength (MPa)	Flexural Strength (MPa)	Fracture Energy Gf (Joule/m²)	Peak Load (3 cm section) (kN)
N0	30	4	200	1.9
N1	105	18,02	6134	2.35
N2	95	21.12	6081	2.74
N3	107	24,5	8779	4.7
N4	120	25.46	8267	2.55
N5	110	24	8680	31
N6	65	7	1991	2.7
N7	102	5,08	36	16
N8	53	7,03	84	14
N9	77	5,67	735	9
N10	80	4.84	1335	9.47
N11	103	22	8482	12.39
N12	78	4.48	1218	3.865
N13	107	24.5	8654	14.4

Table 3 provides valuable insights into the structural performance of various concrete mixtures by comparing their mechanical properties. Parameters such as compressive strength, flexural strength, fracture energy, and peak load shed light on the behaviour of concrete under different loads. The compressive strength represents the concrete's resistance to compression, whereas the flexural strength indicates its resistance to bending. Fracture energy is a measure of concrete crack resistance, with higher values indicating more durable concrete. The peak load is the maximum load a concrete specimen can withstand. By analysing these parameters, the suitability of different concrete mixtures for structural applications can be assessed, and the most optimal mixture can be selected.

Figure 2. Wooden mould prepared for prototype casting.

The data obtained from the mechanical tests conducted on specimens produced with concrete mixtures prepared at different material ratios enabled us to design the wooden mould shown in Figure 2 for casting thin-section concrete urban furniture. Thanks to these tests, we determined the most suitable concrete mixture for the production of urban furniture by comparing the strength, flexibility, and other properties of different concrete mixtures. As a result of detailed examinations conducted on specimens produced with the most suitable concrete mixture determined, a mould was designed for a thin-section concrete urban furniture prototype, and prototype production was started.

Figure 3. Shows the prototype product extracted from the mould on the left, and the physical loads applied to it on the right.

The mould was filled with concrete at the determined optimal concrete-mixture ratios, and the product was removed from the mould. This process was carried out to evaluate the properties of the selected concrete mixture, such as fluidity, setting time, and ease of mould removal. The obtained product was then subjected to physical loading.

3.2. Digital Simulation Results

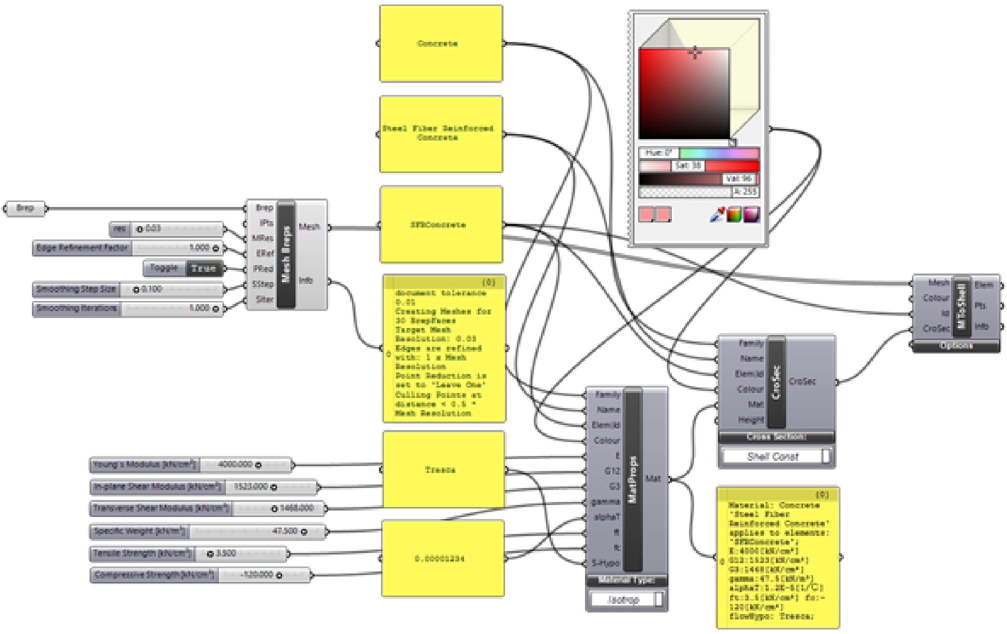
In this study, a comprehensive process was followed for the design, analysis, and optimisation of urban furniture produced using steel fibre reinforced concrete. In this process, which was carried out using Rhino 3D, Grasshopper, and Karamba3D software, both geometric modelling and structural analyses were combined.

Figure 4. Three designs for thin-section urban furniture.

Various urban furniture designs were modelled in 3D in a Rhino 3D environment. Among the designs shown in Figure 4 above, the design shown in Figure 5 below was selected as the most suitable for production and converted to Brep format to be subjected to a more detailed analysis due to Grasshopper’s parametric design capabilities. The Brep object was converted into a mesh structure that was compatible with the Karamba3D add-on and prepared for finite element analysis.

Figure 5. Design selected for the production of a thin-section urban furniture prototype.

The material properties of the SFRC were defined in detail using Karamba3D software. Mechanical properties such as Young’s modulus, shear modulus, specific weight, tensile strength, and compressive strength were added to the material library and used in the model. Considering that the urban furniture will exhibit shell behaviour, the cross-sectional properties of the model were defined with the "Shell Const" component in Figure 6 and converted into a shell element using the "Mesh to Shell" component to prepare it for analysis.



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0.01
Creating Meshes for
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Target Mesh
Resolution: 0.03
Edges are refined
with: 1 x Mesh
Resolution
Point Reduction is
set to 'Leave One'
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distance < 0.5 *
Mesh Resolution
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Reinforced Concrete'
applies to elements:
'SFRConcrete';
E:4000[kN/cm²]
G12:1523[kN/cm²]
G3:1468[kN/cm²]
gamma:47.5[kN/m³]
alphaT:1.2E-5[1/C]
ft:3.5[kN/cm²] fc:-
120[kN/cm²]
flowHypo: Tresca;
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Figure 6. Three designs for thin-section urban furniture are presented below.

Thanks to the “Assemble” component in Karamba3D, the geometric model was transformed into a structural system, considering the loads, boundary conditions, and material properties. The AnalyseThII component processed this numerical model to determine the static and dynamic behaviours of the structure. In this analysis, the engineering results, such as the stress, deformation, and displacement caused by the loads on the model, were calculated.

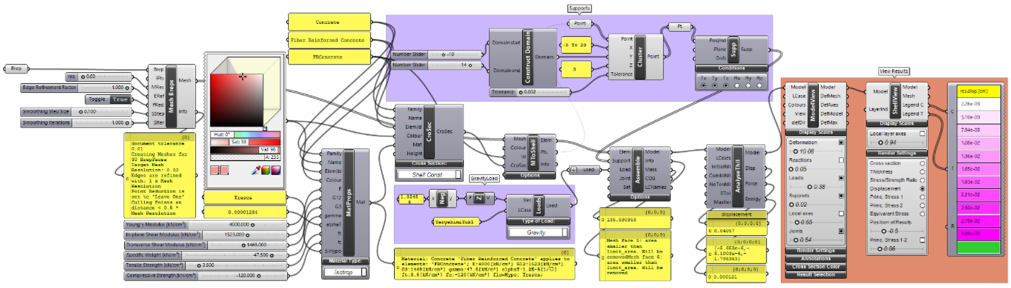

Figure 7. The model was tested digitally after adding all the parameters of the digital simulation.

The analysis results shown in Figure 7 above have been visualised using the "ModelView" and "ShellView" components. In this way, the most critical regions of the structure were identified, and the safety and durability of the design were evaluated. The numerical results obtained were validated by comparing them with data obtained from experimental studies, and the reliability of the model was determined.

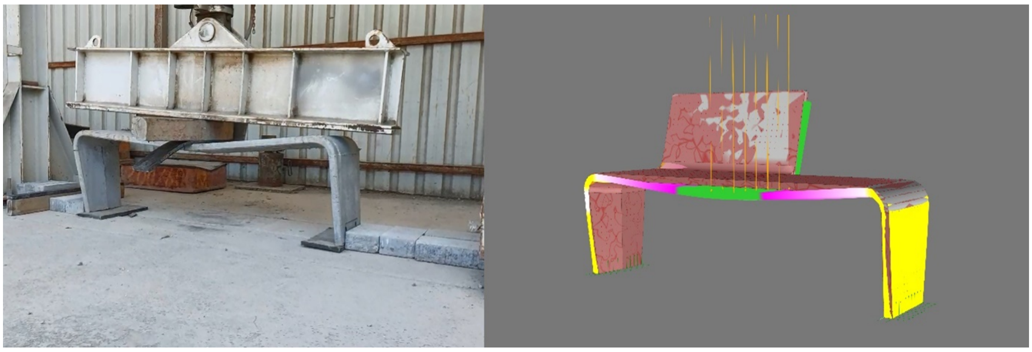

Figure 8. Shows three different designs designed for thin-section urban furniture.

In Figure 8, the maximum load-carrying capacity of the prototype product was experimentally determined by applying a linear load to a point near the predetermined weak region in the numerical model of the prototype product. The experimental data were also simulated in the numerical model, and the physical and numerical results were compared. The results confirmed that the numerical model realistically simulated the mechanical behaviour of the product by showing a similar failure or deformation behaviour in both the physical prototype and the numerical model. Consequently, more definitive results were obtained regarding the reliability and durability of the product design.

4. Discussion

In this study, the potential of using steel fibre reinforced concrete in urban furniture was investigated using experimental and numerical methods. The results of this study show that SFRC offers higher strength, ductility, and crack-delaying properties than traditional concrete. The findings provide strong support for the use of SFRC in urban furniture. In particular, the behaviour of SFRCs for structural elements with different geometries has been successfully modelled using digital simulations, and the experimental results have been verified. This situation indicates that the SFRC will make significant contributions to modern design principles such as aesthetics and durability. In this study, we observed that the steel fibre ratio had an unexpected effect on the mechanical properties of concrete. This indicates that the complex interactions of steel fibres within the concrete matrix require further investigation. While studies on SFRC in the existing literature have mostly focused on structural elements, this study has filled the gap in the field by conducting a more in-depth examination of the specific application of SFRC to urban furniture. Another unique aspect of the study is the use of digital design tools and their verification using experimental results. In this way, the behaviour of SFRCs in structural elements with different geometries was better understood, and a new perspective was offered for design processes. Although this study on steel fibre reinforced concrete sheds light on an important issue, it has some limitations. Experiments conducted on a limited number of mixtures and geometric shapes restrict the generalizability of the results. In addition, critical issues such as the long-term behaviour of the SFRC and its performance under different environmental conditions have not been investigated in detail. One of the most significant limitations of this study is the use of a limited number of samples. This situation does not provide sufficient data to obtain statistically significant results, making it difficult for us to conclude that the results are valid for all SFRC mixtures. In addition, the used material models do not fully reflect the complex interactions of steel fibres within the concrete matrix. In particular, at high stress levels and under complex loading conditions, the model results may differ significantly from the behaviour of the real material. This can create uncertainty in the design process and pose risks to the safety of the structure. Another limitation is that the study was conducted under laboratory conditions. The loading conditions applied in the laboratory environment differ from real-life conditions. Therefore, it may not be appropriate to directly apply the obtained results to the structure. The long-term behaviour of steel fibre reinforced concrete and the effects of different environmental conditions were not investigated. Factors such as corrosion, abrasion, and temperature changes are important parameters that can affect the strength and lifespan of a material. In particular, this is a significant deficiency in outdoor applications. Although the results of the research are promising, further studies need to be conducted to better understand the potential of steel fibre reinforced concrete and to enable its wider use in the construction sector. First, a systematic investigation of different types and ratios of steel fibres and experiments on a larger sample pool will increase the general validity of the obtained results. In this way, the most suitable steel fibre combinations for different applications can be determined. In addition, more accurate results can be obtained in load distribution analyses by using advanced material models that better reflect the real material behaviour, and design processes can be optimised. Another important limitation of the study is the lack of experiments conducted under conditions close to real-use conditions. Experiments conducted under different load combinations and environmental effects can better reveal the real performance of the materials. In particular, it is of great importance to conduct long-term experiments to investigate the long-term behaviour of steel fibre concrete and to examine the effects of different environmental conditions on the properties of concrete. Finally, a cost–benefit analysis should be conducted by comparing the initial cost of steel fibre reinforced concrete with the economic advantages it offers in the long term. In this way, a clearer idea about the economic feasibility of the material can be obtained, and more reliable data can be presented to investors. Studies conducted in line with these recommendations will expand the use of reinforced steel concrete in the construction sector and contribute to the construction of more sustainable structures. In conclusion, this study provides a strong foundation for the use of SFRC in urban furniture. The results of this study show that the SFRC has significant potential for the design of aesthetic and durable urban furniture. However, more comprehensive studies are needed, and further research is needed to apply the findings to different projects. By fully realising the potential of the SFRC, more sustainable and economical solutions can be offered.

5. Conclusions

In this study, the use of steel fibre reinforced concrete in urban furniture was investigated through experimental and numerical analyses. The results show that SFRC exhibits superior performance to traditional concrete. In particular, properties such as high strength, ductility, and crack resistance support the conclusion that the use of SFRC in urban furniture can extend the life of these structures and reduce maintenance costs. Numerical simulations have successfully modelled the behaviour of SFRCs for structural elements with different geometries, making the design process more efficient and cost-effective. One of the significant findings of the study is the determination that the SFRC can contribute to modern urban design principles such as aesthetics and durability. The lightness and aesthetic features of SFRC make it attractive for use in furniture designs with thin sections and complex geometries. In addition, the high energy absorption capacity of SFRCs enables the design of structures that are resistant to natural disasters such as earthquakes. This research has filled a gap in the literature by highlighting the potential use of SFRC in urban furniture. The findings provide new material alternatives for engineers and designers. However, the use of a limited number of samples and simplified material models limits the generalizability of the results. Issues such as long-term durability and environmental effects were not investigated in depth in this study. In future studies, the effects of different types, sizes, and ratios of steel fibres to SFRC. At the same time, it is important to conduct studies that examine the behaviour of SFRCs under various climatic conditions and long-term use. The development of models capable of predicting the properties of SFRC more accurately using technologies such as artificial intelligence and machine learning offers potential for future research. In conclusion, this study presents significant findings on the usability of SFRC in urban furniture and provides a new perspective on design processes. However, there is a clear need for more experimental and numerical research in this area.

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