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Research Article

Performance of Concrete Sheet Piles with Stranded Steel Waste Using Finite Element Method

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Abstract

The innovation in precast industrial metal waste-based concrete materials aims to improve the mechanical properties of concrete while reducing its environmental impact. This study examined the performance of 62.25 MPa plain concrete sheet piles with the addition of steel fiber waste through finite element method (FEM)-based numerical modelling with a cantilever configuration that represents actual field conditions used linear modelling. The variations in the steel fiber waste content analyzed were 0%, 1%, 2%, 3%, and 4%. The test specimens were modelled with modified dimensions (50 × 20 × 10 cm) to accommodate the computational limitations. The material parameters refer to the SNI standard, where the elastic modulus of concrete is calculated using an empirical approach, and the steel fiber is modelled as an isotropic elastic material with mechanical properties according to the standard. The analysis focused on the deflection behavior, moment capacity, and deformation response to a design load of 41.5 kN. The simulation results showed that additional 1% strand content produced deflections that were within safe limits (≤ 2.8 mm). The lowest deflection value occurred in the 1% variation, with a decrease of 7.89% compared with normal concrete. Increasing the strand content above 1% did not provide significant additional benefits; in fact, at a content of 4%, the deflection increased by 5.57%. This indicates that an increase in fiber distribution density can reduce the homogeneity of concrete that potentially create weak zones in concrete. Thus, this study confirmed that adding 1% steel fiber waste is optimal for improving the flexural deformation performance of concrete sheet piles.

Keywords: *steel fiber waste, mechanical properties of concrete, concrete sheet pile, finite element method.*

1. INTRODUCTION

The need for durable and environmentally friendly construction materials has driven innovation in concrete engineering. Despite its high compressive strength, conventional concrete faces challenges in terms of low ductility and crack resistance [1]. As awareness of sustainability increases, various studies are attempting to utilize industrial metal waste as concrete reinforcement, not only to improve mechanical performance but also to reduce the environmental impact of solid waste [2].

Over the past decade, the use of steel strand waste and steel fibers in concrete mixtures has yielded promising results. Augustino et al. [3] showed that the use of steel fibers from used tires can increase the compressive and flexural strengths of concrete by up to 49% at a content of 1.35%. A follow-up study by Sakthivel & Vijay Aravind [4] confirmed that fiber contents below 2% provide a significant increase in crack resistance without reducing the workability of the concrete.

Similar findings were reported in a study on the basic mechanical properties of waste steel fiber-reinforced concrete after high-temperature exposure, which showed that at a concentration of 1% waste steel fiber, concrete experienced an increase in compressive strength of ±10% even after exposure to high temperatures [5]. Conversely, fiber content above 2% causes fiber clustering and reduces the homogeneity of concrete [6]. This pattern shows that there is an optimum level of waste steel use that is not only structurally useful but also economical and environmentally friendly.

Sheet piles are soil-retaining elements that operate based on the cantilever principle. In field

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applications, such as slope protection, ports, and retaining walls, these elements face a complex combination of bending, shear, and lateral soil pressure forces [7]. Therefore, reinforcing the sheet pile concrete is crucial to ensure long-term stability.

The development of the finite element method (FEM) provides opportunities to analyze the behavior of concrete in greater detail before conducting experiments. Using FEM, researchers can efficiently predict the deformation, bending moments, and internal stresses in structural elements, as this method divides the structure into small elements that can be numerically analyses for complex load responses [8]. This approach has been used in various studies to model fiber-reinforced concrete [9], which showed high accuracy compared to the experimental data.

In the context of sheet piles, a study by Kustiwa et al. [10] compared the results of 2D and 3D FEM analyses on sheet pile structures and found significant differences in the stress distribution and safety factors. These findings emphasize the importance of the FEM in evaluating the behavior of complex structures, such as sheet piles.

Table 1. Previous research

Research	Focus Material	Fiber Content	Key Findings	Relevance to This Study
Agustino et al. (2022)	High-quality concrete with recycled steel fibers	0,3–1,35%	Up to 49% increase in compressive strength	Demonstrating the potential for steel waste strengthening
Yang et al. (2025)	C40–C60 concrete with steel waste fibers	1–2%	Optimal at 1% with +10% compressive strength	The optimal level is similar to this study
Zeybek et al. (2022)	Concrete with steel fibers from waste tires	1–3%	Slump test above 2%	Supporting maximum level evaluation
Srikanth et al. (2022)	FEM fiber concrete	-	Accurate stress prediction	Relevant from a methodological perspective
Tikanta et al. (2017)	Sheet piles for bridge foundations	-	Effective numerical FEM validation	The basis for applying the model in this study

Based on the literature, most studies on concrete with steel waste still focus on laboratory-scale mechanical testing and have not yet reached large-scale structural elements, such as sheet piles. In addition, most FEM studies on sheet piles do not highlight sustainable material modifications.

This study attempts to bridge these two gaps by performing numerical modelling of 62.25 MPa concrete sheet piles with varying steel fiber waste contents (0–4%) using the finite element method on the SimScale platform. The analysis focused on the effect of the strand content on the deflection and flexural stress distribution. The results are expected to serve as an initial reference for developing sustainable concrete sheet pile designs that are structurally efficient and environmentally friendly.

2. METHODOLOGY

Model Design and Material Parameter

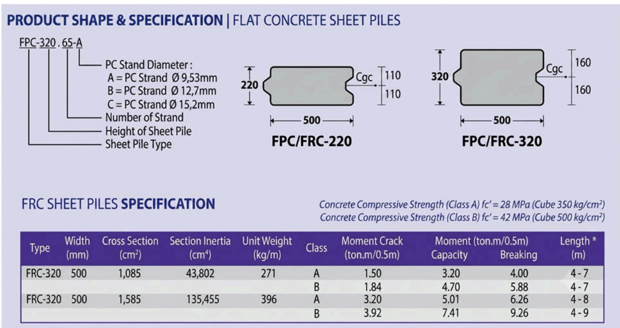
The test object/sample was a sheet pile modified from the Waskita Beton Flat Reinforced Concrete Sheet Pile type, as shown in Figure 1. The concrete is modelled as plain concrete and the dimensions were adjusted to be computationally efficient while still representing the original proportions. The test specimen specifications are presented in Table 2 where concrete using SNI 2847:2019 [11] and Steel Strand SNI 1729:2002 [12]

- Length *(L)* : 500 mm
- Width *(b)* : 200 mm
- Thickness *(h)* : 100 mm
- Concrete cover thickness : 20 mm
- Concrete grade : *fc'* = 62.25 MPa
- Type of support : single-sided clamp (cantilever sheet pile)

The variations in the steel fiber waste content were 0%, 1%, 2%, 3%, and 4% of the total concrete volume, respectively. Steel fiber waste (strand) was modelled as linear elastic cylindrical rods with a diameter of 3 mm and a length of 70 mm as discrete reinforcement elements embedded in the concrete matrix and randomly distributed within the concrete volume without slip interaction (perfect bond assumtion).

Table 2. Main parameters

Materials	Parameters	Values	References
Concrete	Elastic Modulus	37,082 MPa	SNI 2847:2019
	Density	2,400 kg/m^3	PPPURG 1987
Steel Strand	Elastic Modulus	210,000 Mpa	SNI 1729:2002
	Density	7,850 kg/m^3	PPPURG 1987



Type	Width (mm)	Cross Section (cm^2)	Section Inertia (cm^4)	Unit Weight (kg/m)	Class	Moment Crack (ton.m/0.5m)	Moment (ton.m/0.5m) Capacity	Moment (ton.m/0.5m) Breaking	Length * (m)
FRC-320	500	1,085	43,802	271	A	1.50	3.20	4.00	4 - 7
					B	1.84	4.70	5.88	4 - 7
FRC-320	500	1,585	135,455	396	A	3.20	5.01	6.26	4 - 8
					B	3.92	7.41	9.26	4 - 9

Figure 1. Specification product of Waskita Beton

Based on Figure 1, the size of the original test object was quite large, the length 10,000 mm, with width 500 mm and thickness 220 mm for type FPC/FCR-220 class A. This results in difficulties in simulations. The limitations of this simulation require modifications to the test objects used. These modifications include dimension reduction from

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original size with scales 1 : 11. The modified test object is shown in Figure 2.

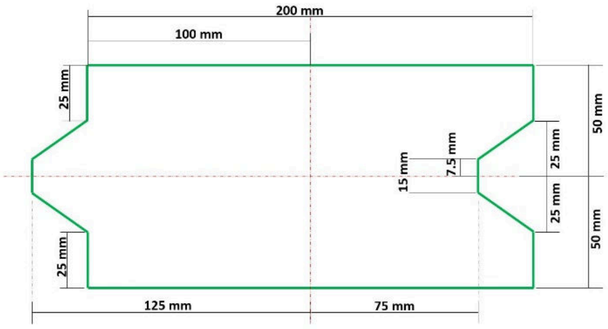
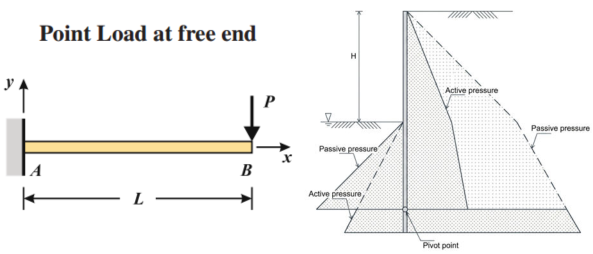


Figure 2. Modified test object

The length of the sample in Figure 2 is 500 mm, with a width of 200 mm and thickness of 100 mm. Five types of samples were used in this study.

The design of the test object support is shown in Figure 3 (a). This is based on the active soil pressure graph using the fixed-end equilibrium method. The soil pressure diagram using the fixed-end equilibrium method is shown in Figure 3(b).



(a) (b)

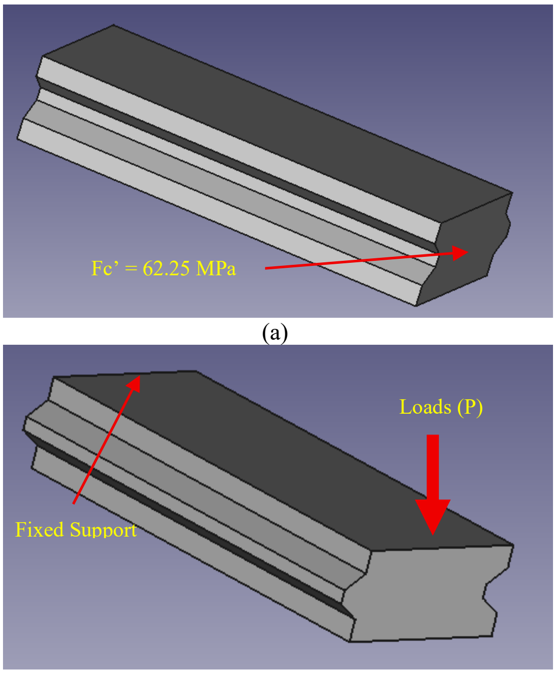
Figure 3. (a) Test object support design [13] and (b) Soil pressure diagram fixed end method (SNI 8460:2017) [14]

The types of samples used are presented in the table below.

Table 3. Variations in strand steel content

Test Object	Steel Fiber Waste Percentage	Number of Strands
SFRC 0 %	0%	0
SFRC 1 %	1%	62
SFRC 2 %	2%	124
SFRC 3 %	3%	186
SFRC 4 %	4%	248

Based on **Error! Reference source not found.**, the test object with the highest number of steel strands was the 4%-SFRC sample with 248 strands. Parts of the sample are shown in Figure 4(a) and Figure 4(b). The bearing position and loading on sheet pile object test explained where the design load is at the free end which is denoted by the load "P" and fix support position.



(a)

(b)

Figure 4. (a) SFRC 0% and (b) Bearing position and loading

Based on Figure 4, this sample had 0% SFRC with loading condition. Meanwhile, the sample with 1% SFRC and others had an additional component, which was steel fiber waste. The 1% SFRC samples are shown in Figure 5.

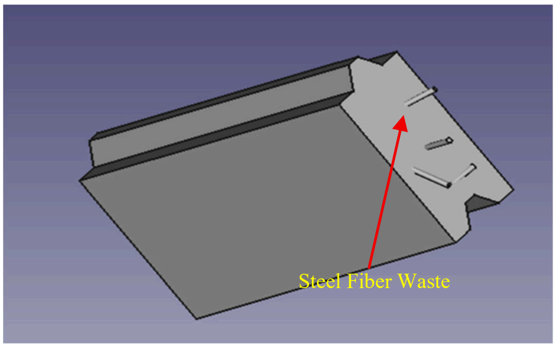


Figure 5. SFRC 1% Test object

Based on Figure 5, it can be seen that there are additional materials. The type of testing uses a cantilever.

FEM Modelling

The modelling was performed using the SimScale cloud-based software that supports FEM numerical solutions for 3D solid elements. The modelling stages consisted of the following:

a) The sheet pile geometry was created as a 3D block with a length of 500 mm, width of 200 mm, and thickness of 100 mm. Strand variations were added parametrically with 0, 62, 124, 186, and 248 bars according to a content of 0–4% of volume.

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b) The concrete was modeled as plain concrete with additional embedded strands, without conventional reinforcement. Each strand was assigned a constant diameter of 3 mm and modeled as a discrete element embedded within the concrete matrix
c) The strands distributed automatically using a stochastic algorithm based on the specified reinforcement content. To minimize the influence of spatial variability, multiple random realizations were generated for each reinforcement level using different random seeds. The reported results represent the average response of these realizations, ensuring that the observed trends are not dependent on a specific strand configuration
d) A tetrahedral mesh with an element size of 5 mm was used to maintain a balance between accuracy and computation time.
e) One side of the sheet pile was set as a fixed support, and a static load was applied evenly to the free end according to the working conditions in the field explain in (b).
f) The analysis is done using linear modeling.

3. RESULT AND DISCUSSION

Load Analysis on Sheet Pile

The calculation analysis was based on the strength of the concrete to withstand the loads. The applied load can result in a specific moment. The following data were used to analyze the loading on the sheet piles. The deflection analysis of the test object is as follows:

Length = 500 mm
Width = 200 mm
Thickness = 100 mm
Capacity Analysis:

$$s = \frac{bh^2}{6} = \frac{2x10^6}{6} = 333333.33 \text{ mm}^3$$

$$M_u = \sigma \; x \; s$$
$$= 62{,}25 \text{ x } 333333{,}33$$
$$= 20750000 \text{ N.mm}$$
$$= 20.75 \text{ kN.m}$$

$$P = \frac{Mu}{L} = \frac{20.75}{0.5} = 41.5 \text{ kN}$$

Maximum Deflection Analysis :

D max = 0.5% x L (SNI 8460:2017)
= 0.005 x 500
= 2.5 mm

D max $= \frac{PL^3}{3EI}$ (Leckie & Bello, 2009)
= 2.8 mm

The calculation results showed a planned load value of 41.5 kN with a maximum deflection of 2.8 mm.

FEM Simulation Result

Without Steel Fiber Waste (SFRC 0%)

As in the calculation of point D, the load applied was 41.5 kN. Based on the calculation, the maximum deflection value for the sheet pile was 2.8 mm. The results of the simulation are shown in Figure 6.

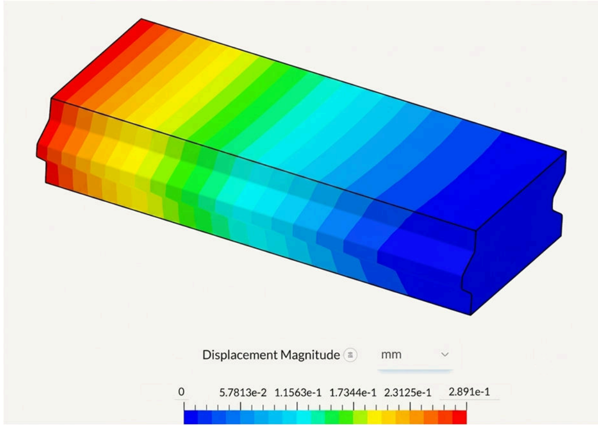
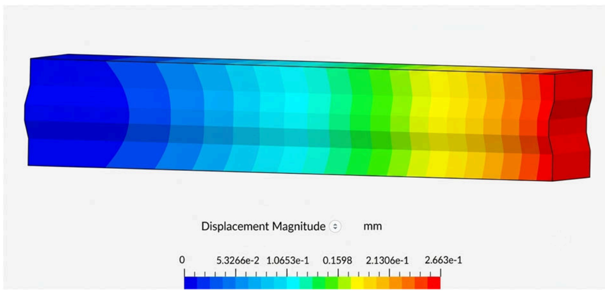


Figure 6. Displacement SFRC 0%

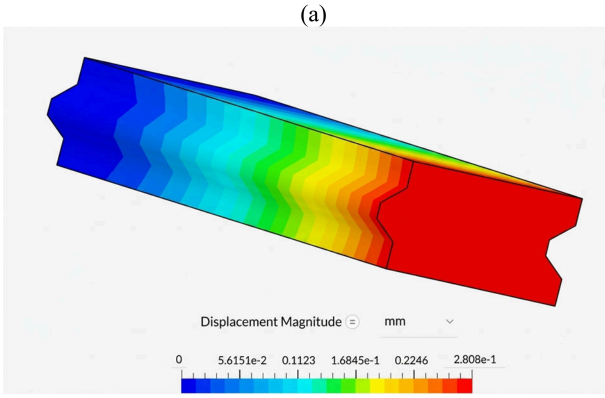
As shown in **Error! Reference source not found.**, the deflection value is 2.891 mm. The moment was 20.75 kN.m. This is still safe because the maximum deflection that occurs is less than 2.8 mm ($\frac{PL^3}{3EI}$).

Additional 1%, 2%, 3%, and 4% Steel Fiber Waste (SFRC 1%-4%)

As in the calculation at point D, the load applied was planned to be 41.5 kN. Based on the calculation, the maximum deflection value for the sheet pile is 2.8 mm. The results of the simulation are shown in Error! Reference source not found..



(a)



(b)

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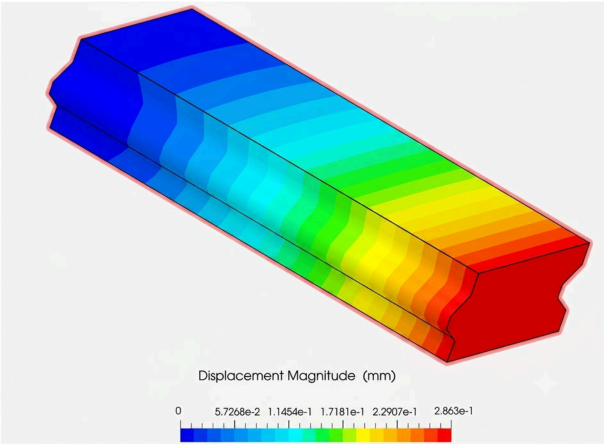
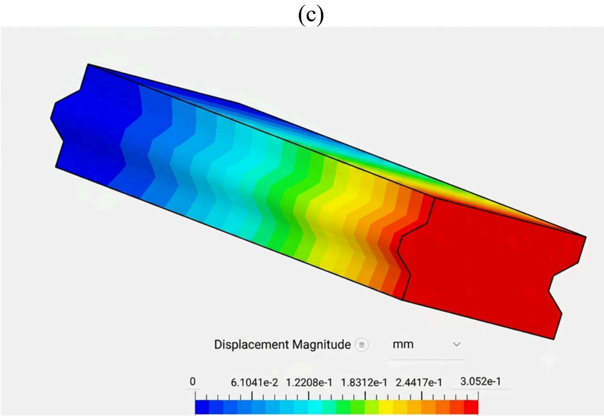


(c)



(d)

Figure 7. (a) Displacement SFRC 1%, (b) Displacement SFRC 2%, (c) Displacement SFRC 3% and (d) Displacement SFRC 4%

As shown in Figure 7, the SFRC deflection values from 1% to 4% are 2.663, 2.808, 2.863, and 3.052 mm, respectively, and the moment is 20.75 kN.m. For SFRC at 1%, the values were less than the maximum deflection, and the rest of it was not safe because the maximum deflection that occurred exceeded 2.8 mm.

The Relationship Between Deflection and Variations in Steel Fiber Waste

After conducting simulations and obtaining the deflection results, the graph showing the relationship between deflection and the percentage of strand steel added to demonstrate the trend of this model is shown in Figure 8 and Table 4.

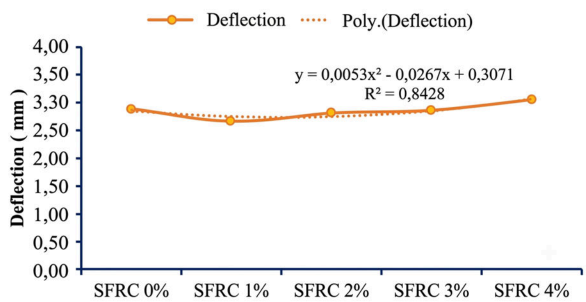


Figure 8. Deflection graph with variations in steel fiber waste

Table 4. Comparison of deflection with variations in steel fiber waste

Mix	Deflection (mm)	Percentage Difference
SFRC 0 %	2.891	0.00 %
SFRC 1 %	2.663	7.89 %
SFRC 2 %	2.808	2.87 %
SFRC 3 %	2.863	0.97 %
SFRC 4 %	3.052	-5.57 %

Table 4 and Figure 8 show the comparison of deflection with variations in steel fiber waste, and it was found that 1% SFRC concrete experienced the smallest deflection of 2.663 mm with a percentage increase in deflection of 7.89%. The numerical results show that the deflection of testing object decreases with add 1% strand content but increases at 2-4%, it demonstrate strand density can create weakzone in concrete disting to previous experimental and numerical studies on reinforced and composite cantilever beams, where additional reinforcement significantly enhances flexural stiffness and reduces deflection [15].

4. CONCLUSION

Based on the results of this study, the following conclusions were drawn:

a) concrete sheet pile models, with 1% the addition of steel fiber waste, showed deflection that was still within safe limits according to Leckie & Bello, 2009, namely deflection $\leq (\frac{PL^3}{3EI})$ of the element length (2.8 mm).
b) A Steel Fiber Waste content of 1% provided the smallest structural performance, with a maximum deflection reduction of 7.89% compared to plain concrete.
c) The addition of more than 1% strands no longer increases stiffness; on the contrary, it causes an increase in deflection and stress concentration around the fiber area. This indicates that an increase in fiber distribution density can reduce the homogeneity of concrete and potentially create weakzone.
d) The stress distribution results from FEM show that the critical zone is located at the fixed support, with a decreasing stress pattern at 1% content and an increase again at high contents.
e) The FEM approach demonstrates the capability to capture the general flexural behaviour of concrete sheet piles and provides predictive insights within the assumptions of the model. However, the absence of direct experimental validation remains a limitation.

Recommendations for future research include the need for laboratory-based experimental validation based on FEM testing.

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