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Analysis of the use of fiber concrete in lintel beams as an alternative to traditional prefabricated solutions

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Abstract: Sustainable construction focuses on minimizing raw material consumption and optimizing construction processes in terms of both economy and ecology. Lintels are among the structural elements where material usage can be significantly reduced. Traditionally used prefabricated beams, while convenient, often exhibit excessive strength relative to actual loads, leading to unnecessary costs and an increased carbon footprint. This article examines the potential use of fiber-reinforced concrete – concrete strengthened with polymer and steel fibers – as an alternative to traditional lintels. Comparative strength tests were conducted on four beam variants, including those reinforced with fiber reinforcement. The results indicate that despite having a lower load-bearing capacity compared to prefabricated beams, fiber-reinforced concrete can be a viable option in certain scenarios, particularly where lintels do not serve a primary load-bearing function. Additionally, the article aligns with contemporary construction trends, such as the use of waste materials in concrete reinforcement, by considering the incorporation of plastic fibers as an alternative to traditional steel reinforcement. The use of recycled fibers – including plastics, reclaimed steel, and carbon fibers from the aerospace and automotive industries – can enhance the mechanical properties of concrete while reducing its environmental impact. These innovations align with the principles of the circular economy, providing both ecological and economic benefits. The research findings suggest that fiber-reinforced concrete lintels can contribute to reducing construction costs and limiting the consumption of natural resources, making them a compelling alternative to conventional solutions.

Keywords: lintel beam, fiber concrete, sustainable construction, material optimization, concrete strength

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Introduction

Sustainable construction (green building) focuses on designing and constructing structures in a way that minimizes environmental impact (Kysiak & Szuba, 2023). Key aspects of this approach include selecting eco-friendly materials and reducing raw material consumption (Kobaka & Katzer, 2022; Vighio et al., 2024). One important step towards improving construction efficiency is optimizing structural elements, such as lintels.

In building construction, lintels serve as horizontal structural elements that span openings in walls, such as doors or windows. Their primary function is to transfer the load of the masonry above the opening to the surrounding wall through flexural action, preventing excessive stress on door and window frames. As a crucial component of wall construction, lintels can be optimized in terms of both materials and costs. This not only provides significant benefits for small construction companies but also offers a way to stand out in local markets (Respondek, 2017).

Although prefabricated beams are commonly used in traditional construction, they often prove economically unjustified due to their excessive load-bearing capacity. A promising alternative is fiber-reinforced concrete, which offers good mechanical properties while simultaneously reducing costs and raw material consumption.

History and development of lintels

Throughout history, primitive societies and early civilizations employed various techniques for constructing lintels. One of the oldest and simplest methods involved using large, flat stones. Examples of this technique include megalithic structures such as: Stonehenge (ca. 3000-2000 BC), where horizontal stones functioned as lintels atop vertical menhirs; and the Cyclopean structures of Mycenae (16th-11th centuries BC) such as the Lion Gate, where massive stone blocks formed primitive lintels. In forested regions, wooden beams were commonly used as lintels. Examples include stilt houses in marshy areas, such as those found on lakes in the Swiss Alps. In desert and hot regions, such as Mesopotamia, Egypt, and South America, builders used sun-dried clay bricks (adobe) or rammed earth for lintels. Sumerian architecture (ca. 4000 BC) featured lintels made of sun-dried bricks reinforced with clay mortar.

Primitive communities that constructed huts using the wattle and daub technique – where woven branches or wooden beams were coated with clay – also developed lintels in this manner, as seen in Neolithic buildings in Europe and traditional savannah houses in Africa. In Arctic hunter-gatherer societies, large animal bones, such as mammoth bones, were sometimes used as lintels. Evidence of this can be found in mammoth bone shelters in Ukraine (ca. 15,000-10,000 BC), where bones were arranged in arch-like formations and reinforced with hides and clay.

In summary, early civilizations used the materials available in their surroundings – ranging from stone and wood to clay and bones – to construct lintels. As technology advanced, more sophisticated methods, such as arched and brick lintels, emerged, laying the foundation for modern architectural solutions.

Modern technologies in lintel construction

Currently, flat lintels are the most commonly designed type. There are several methods for constructing flat lintels, including brick lintels, reinforced with steel inserts, steel beam lintels, and prefabricated reinforced concrete elements. The choice of a specific solution depends on the span of the opening to be covered and the loads acting on the lintel.

The computational static scheme of a lintel is modeled as a freely supported beam with an effective span l_{eff}, which increases the opening width by 5 %. The load acting on the lintel beam is unevenly distributed. In more complex cases, an equivalent uniformly distributed load is used. The principles for determining the equivalent load can be found, for example (Hoła et al., 2010).

For the purposes of this analysis, a lintel is considered above a door opening in an internal wall. The building's load-bearing structure is assumed to be a column-ceiling system, where masonry walls serve as infill walls and are structurally separated from the ceiling or beam above. Assuming that no more than 0.5 m of the 18 cm thick wall remains above the beam, the calculated load intensity on the beam was determined to be 2.99 kN/m. In the most unfavorable case, a 25 cm thick solid brick wall can be assumed, increasing the load to 3.83 kN/m. In both cases, the dead weight of the reinforced concrete beam with a cross-section of 18×19 cm, with a minimum value of 0.41 kN/m, was considered. Figure 1 shows how the value of the design moment (M_{Ed}) changes depending on the beam span. The solid red line represents the weight of an 18 cm thick wall, while the red dashed line indicates the more unfavorable values corresponding to a 25 cm thick wall.

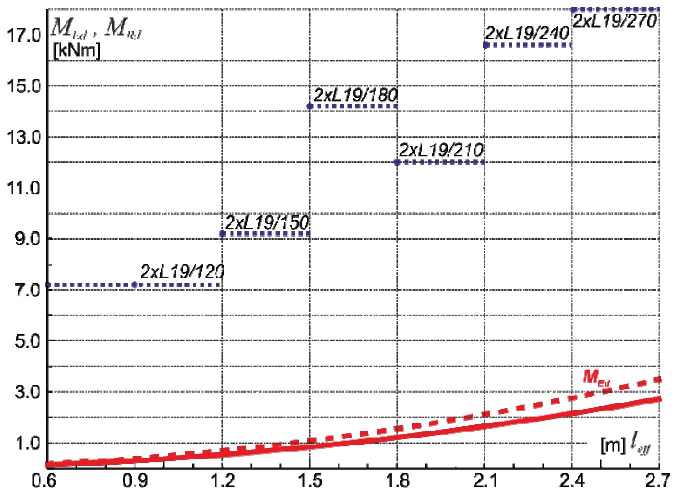

Fig. 1. Dependence of the design moment and load-bearing capacity of prefabricated beams on the opening span. Details are provided in the text (*own research*)

A common solution in most multi-family building constructions is the use of prefabricated lintels. The specifications provided by manufacturers of prefabricated L19 beams (e.g., Betard, Leier) define their design bending capacity M_{Rd} or maximum design load q_d. For wall thicknesses greater than 18 cm, two beams are typically used. The average guaranteed tensile strength of concrete, depending on its class, is as follows: 2.2 MPa for C20/25 concrete, 2.9 MPa for C30/37 concrete, and 3.5 MPa for C40/50 concrete. As shown in Figure 1, for walls serving as non-load-bearing infill elements, a significant excess load capacity is observed (black dashed lines). In such cases, the use of prefabricated lintel beams is economically unjustified.

Reinforced concrete beams poured on-site, in accordance with standard guidelines, should have minimum dimensions of 10×25 cm and be reinforced with two main 12 mm diameter bars, resulting in a design bending capacity M_{Rd} of 8.89 kNm, which is also significantly higher than the required level.

The concept considered in this article is the use of on-site cast beams made from concrete reinforced with dispersed fibers. Mineral composites with dispersed fibers, referred to in this paper as fiber composites, offer numerous advantages. The most significant include:

- Higher compressive strength in the early stages of curing compared to ordinary concrete (Ding & Kusterle, 2000),
- Higher tensile strength (Yazici et al., 2007), including tensile strength in bending and splitting,
- High dynamic resistance (Teng et al., 2008; Wang et al., 2008),
- Limited crack propagation in structural elements (Uygunoglu, 2008),
- Improved failure behavior (Wang et al., 2010), as destruction occurs more gradually,
- Potential for reducing traditional reinforcement (Dobashi et al., 2007),
- High-temperature resistance (Sukontasukkul et al., 2010).

The presence of fibers in the concrete matrix reduces crack width and surface area, enhancing the fiber-reinforced concrete elements' resistance to harmful substances and adverse weather conditions compared to conventional concrete (Blazy et al., 2022; Helbrych, 2021). Additionally, fiber-reinforced concrete lowers costs in both production and maintenance. Its increased ductility, superior resistance to abrasion, water, frost, fire, and impact makes these elements more durable, safer, and better protected against vandalism (Blazy et al., 2022; Pietrzak, 2024). More about the methods for calculating reinforced concrete structures with combined reinforcement can be found in (Selejdak et al., 2023).

With the growing acceptance of sustainable development (Zhang et al., 2021), the concrete market is evolving to incorporate recycled materials (Ma et al., 2022). The range of mineral additives used in concrete has expanded to include new types of raw materials and waste. In cement composite production, various recycled waste materials are utilized, including sanitary and household ceramics (Ulewicz & Halbiniak, 2016), slag and furnace ash (Jura & Ulewicz, 2021), as well as different types of polymer waste and rubber (Pietrzak & Ulewicz, 2023; Purcell et al., 2021; Ulewicz & Pietrzak, 2021; 2023). In recent years, there have also been attempts to apply green composites or biocomposites reinforced with natural fibers to structural elements (Stefanidou et al., 2022). However, the most commonly used dispersed reinforcement materials remain polymer and steel fibers.

1. Strength tests

The influence of structural reinforcement on the mechanical properties of concrete is primarily manifested in crack inhibition and increased energy absorption during failure. The use of fibers in appropriate proportions enhances the tensile and shear strength of concrete (Latifi et al., 2021).

The primary objective of research was to evaluate the suitability of fibers as independent reinforcement for lintel beams. Firstly, three concrete samples measuring 15x15x15 cm were subjected to a compressive strength test. The samples were collected simultaneously with the production of the beams and stored and cured in the same manner. The average compressive strength was 21.3 MPa. Based on the compressive strength test results, the concrete was classified as C16/20. The main study focused on concrete beams with three types of dispersed reinforcement, each measuring 9×19×120 cm, which corresponds to typical prefabricated elements. The selected reinforcements included:

- Polymer fibers: ASTRA Polyex Duro (2 kg/m^3) and ASTRA Polyex MESH 2000 (2 kg/m^3),
- Steel fibers: BAUMIX 60 (20 kg/m^3).

Four beams of each type were fabricated and tested. A four-point bending test was conducted, in which the beams were loaded with a gradually increasing concentrated force until failure. The force applied by the press was transmitted to the beams through a crossbeam with two rollers spaced 35 cm apart (Fig. 2). The beam span was 105 cm. During the deflection tests, displacements were monitored using sensors placed at the center of the beam and on the crossbeam, as well as the impact of fiber presence on stiffness (Czajkowska et al., 2023). Figure 2 shows some samples during the conducted strength tests.

a) b)

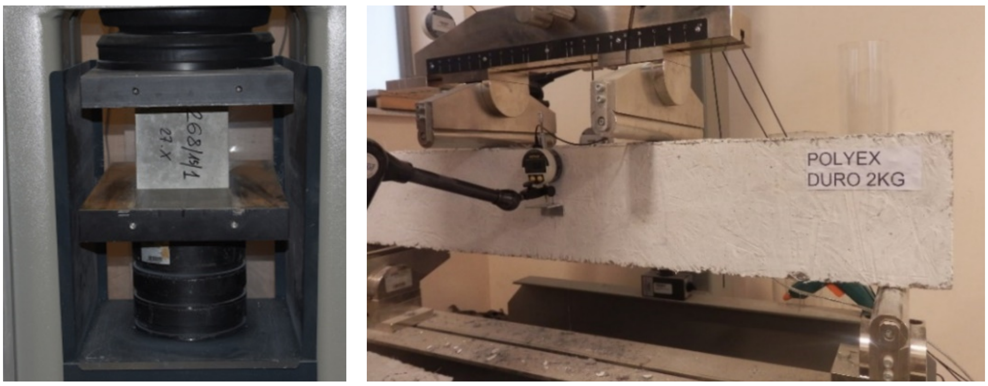

Fig. 2. Laboratory tests: a) compressive strength test b) four-point bending test (*own photos*)

The first set of four-point bending test results consists of the failure load values for beams reinforced exclusively with the three types of fibers mentioned. The purpose of subjecting these beams to bending tests is to compare the force at which failure occurred with the failure load of the catalog L19/9 beam (L = 120 cm) as specified by the manufacturer. This comparison aims to determine whether traditional reinforcement in lintels can be replaced entirely with fiber reinforcement.

Additionally, a concrete beam with a cross-section of 9×19 cm, reinforced with two #12 steel bars (RB500) was fabricated and tested. This result serves as a reference point for comparison. The average values of the failure load and the corresponding failure moment are presented in Table 1.

Table 1. The average values of the failure load and the corresponding failure (*own research*)

	Polyex Duro	Polyex MESH	BAUMIX 60	Concrete beam
	2 kg/m^3	2 kg/m^3	20 kg/m^3	Bars: 2×12 mm
P_{max} [kN]	11.60	10.20	9.86	57.31
M_{max} [kNm]	2.03	1.78	1.72	9.65

2. Analysis of results

In tests of fiber-reinforced concrete samples subjected to bending, cohesive failure is observed, as opposed to brittle failure of ordinary concrete samples (Glinicki, 2008). The fundamental difference in the behavior of both materials under load is the ductility of fiber-reinforced concrete, which allows for the formation of plastic hinges in cracked areas and the redistribution of bending moments. This phenomenon enables greater beam deflection before failure occurs. Taking a cautious approach to these conclusions, a statistical analysis was conducted on all bending test results of beams reinforced with dispersed reinforcement considered to belong to the same class of random events. The result of this statistical analysis is shown in Figure 3, where the density function of the normal distribution is presented alongside a histogram.

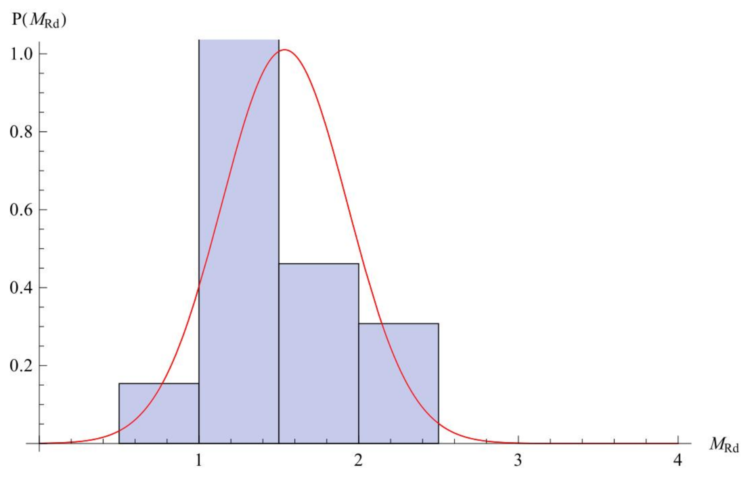

Fig. 3. Histogram of bending tests of fiber-reinforced concrete beams and a graph of the probability density function of the normal distribution (*own research*)

The statistical mean of the failure moments was 1.54 kNm with a coefficient of variation (CV) of 25.7 %. Based on the assumption that the data follows a normal distribution, the 95 % confidence interval ranges from 0.76 kNm to 2.31 kNm. Therefore, the design strength of the beams is taken as 0.76 kNm. Considering the lintel load level according to Figure 1, for the opening corresponding to the tested beam, i.e., with l_{eff} = 1.05 m, the design moment from the applied loads is M_{Ed} = 0.41 kNm. In a wall 18 cm thick, two 9 cm thick beams should be provided, resulting in a beam cross-section utilization of only 27 % (0.41/0.76/2). For a wall 25 cm thick, the moment is M_{Ed} = 0.53 kNm and the degree of utilization increases to only 35 %.

Conclusions

Beams reinforced solely with dispersed reinforcement have a lower load-bearing capacity than commonly used prefabricated beams and therefore cannot be used interchangeably. However, the use of fiber-reinforced concrete in building lintels presents a promising alternative to traditional prefabricated beams. Although their load-bearing capacity is lower, in many cases, their parameters are sufficient – especially where lintels are not subjected to significant loads.

In structural systems where masonry walls are non-load-bearing and are separated from beams or ceilings, the load carried by the lintel comes only from the layers of the wall above it. Producing beams without traditional reinforcement is faster and less complex. By eliminating prefabricated beams, in-house production of fiber-reinforced concrete lintels can significantly reduce costs. When comparing the price of a single prefabricated beam to the cost of the concrete required to cast a similar one on site, we observe a 6 to 10-fold difference. For large-scale projects, this approach may result in substantial savings.

A modern approach to sustainable construction promotes the use of waste materials as concrete reinforcement. Recycled fibers – such as shredded plastics, recycled steel, or carbon fibers from the aerospace and automotive industries – can enhance concrete strength while reducing environmental impact. These solutions align with circular economy principles, offering both economic and ecological benefits. The development of mineral composites enriched with waste fibers could, in the future, lead to significant advancements in the design of structural elements, including lintels.

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