

Modeling and Analysis of Deep Beam using IDEA StatiCa Software

INTRODUCTION

Structural elements are typically classified into Bernoulli (B) and disturbed (D) regions. In a B-region, the flexural strains vary linearly over the section, and well-defined theories are available for designing elements such as beams, columns, and slabs. In contrast, D-regions exhibit a significantly nonlinear strain distribution within the cross-section. This irregularity results from concentrated loads and geometric discontinuities, including pile caps, beam-column joints, frame corners, corbels, deep beams, holes, and supports. Rules-of-thumb or empirical equations are still used in D-region design, although both B and D regions are equally important (Nagarajan & Pillai, 2008).

The strut-and-tie method (STM) is a truss model of structural members comprised of axially loaded struts and ties connected at nodes capable of transferring the factored loads to the supports or adjacent B-regions (ACI, 2019). Recent studies have shown that STM is an effective tool for designing B and D regions. Consequently, several international structural codes and standards, including those from American, European, Canadian, Australian, and New Zealand authorities, recommend using STM for D-region design. However, existing code provisions for designing simply supported deep beams using STM are often inadequate and largely empirical (Silveira et al., 2022).

The main objective of this project is to model and analyze a deep beam using IDEA StatiCa software and validate the accuracy and reliability of the results by comparing them with experimental data from the study "Design and Experimental Investigation of Deep Beams Based on the Generative Tie Method" by Silveira, Paini, and Bitencourt (2022). Moreover, the project aims to assess the effectiveness of

predicting stress flow, developing STM, and evaluating ultimate load capacity and deflection in the deep beam. These findings have practical implications for structural engineering, helping to address challenges such as complex stress conditions, lack of comprehensive models, empirical design approaches, insufficient experimental data, code limitations, and construction and inspection challenges in the design and analysis of deep beams.

DESIGN PARAMETERS

The deep beam specimen was designed using IDEA StatiCa software, inspired by Silveira, Paini, and Bitencourt (2022). It features a span-depth ratio 1.2, with a scale factor of 2 applied to reduce its size. The beam measures 422 cm in length and 49 cm in depth, with a design load (P_d) of 720 kN. It is supported by pin and roller connections and has a specified concrete compressive strength (f'_c) of 40 MPa. The reinforcement cage was built with 10 M, 20 M, 25 M, and 30 M steel bars, each with a yield strength (f_y) of 400 MPa. Details of the Specimen are presented below in Fig.1.

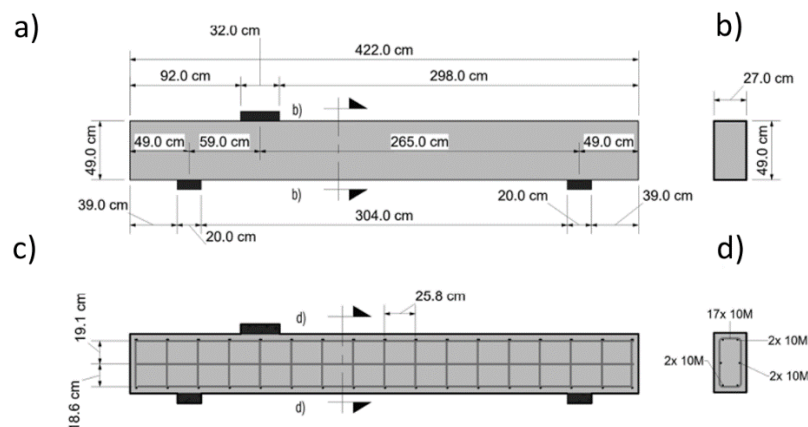


Fig. 1. Studied deep beam: a) side view; b) cross-section; c) side view of the minimum distributed reinforcement detailing; and d) cross-section of the minimum distributed reinforcement detailing.

DESIGN CODES AND SOFTWARE USED

- American Concrete Institute (ACI 318-19) Building Code Requirements for Structural Concrete and Commentary are followed while designing deep beams.
- IDEA StatiCa software developed the model and analyzed the deep beam. It captures the realistic behavior of deep beams using the Component-Based Finite Element Method (CBFEM) and utilizes ACI 318-19 for code-checking and reinforcement design.

Results and Discussion

1. Topology optimization

The primary purpose of topology optimization in IDEA StatiCa for deep beams is to enhance the reinforcement design by determining the most efficient material layout. This method identifies areas of tension and compression within the structure, optimizing material use and enhancing overall structural performance and stability. Such optimization is particularly crucial for elements like deep beams that are subjected to complex load patterns. Fig. 2 illustrates that the blue lines indicate tension regions, while the red lines show compression regions. Ultimately, the aim is to facilitate and accelerate the design of concrete structures, particularly in regions where conventional methods may be inadequate.

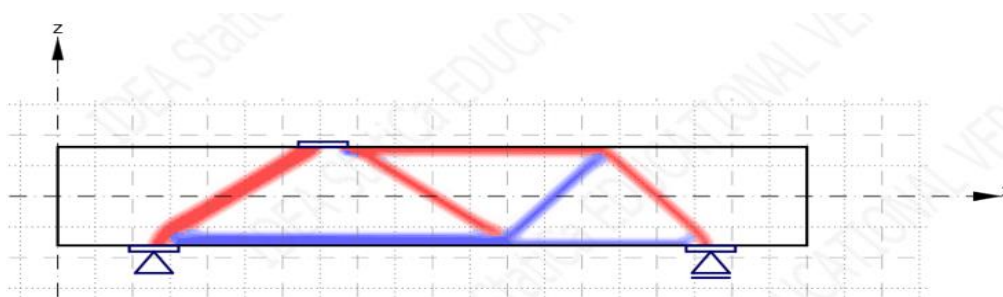


Fig. 2. Topology optimization.

2. Ultimate load capacity

To assess the section's maximum capacity, the test load was progressively increased by 10% for the specimen and the IDEA StatiCa, starting from the design load of 720 kN. The experimental results yielded a maximum load of 1191 kN, while the IDEA StatiCa predicted a maximum load of 1045.3 kN. The ultimate load capacity predicted by IDEA StatiCa generally agreed with the experimental results. The predictions were within a reasonable range of the experimentally recorded ultimate loads, demonstrating IDEA StatiCa's effectiveness in estimating the structural capacity of deep beams.

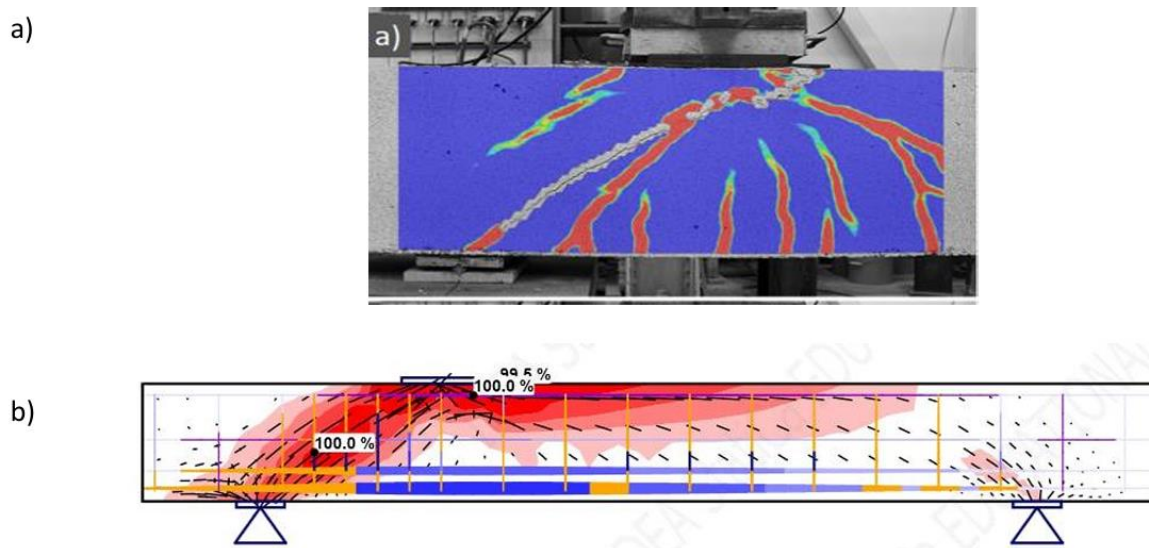


Fig. 3. a) Failure mode of specimen near the support where the load applied at the ultimate load of 1191 KN.

b) Stress flow at the ultimate load from IDEA StatiCa at the ultimate load of 1045.3 KN.

3. Development of strut-and-tie model (STM)

STM idealizes the complex stress flow in a structural member as axial elements in a truss for easy analysis and design. Concrete struts resist compressive stress fields while reinforcing steel ties resist tensile stress fields. Struts and ties intersect at regions called nodes.

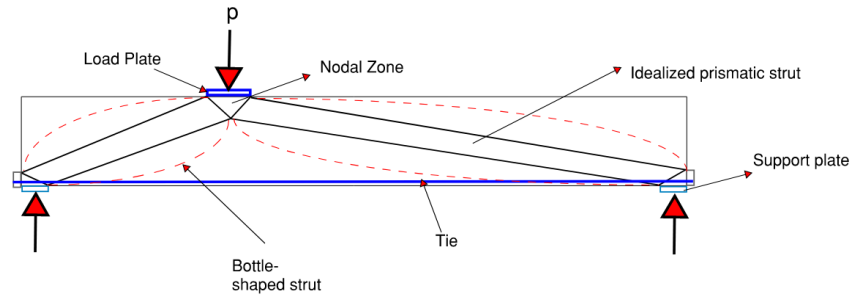


Fig. 4. Strut-and-tie method (STM).

4. Load-deflection behavior

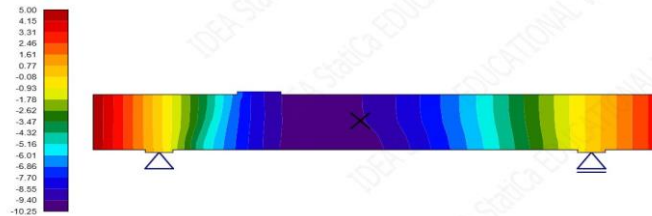


Fig. 5. Vertical deflection profile along the deep beam length predicted by IDEA StatiCa.

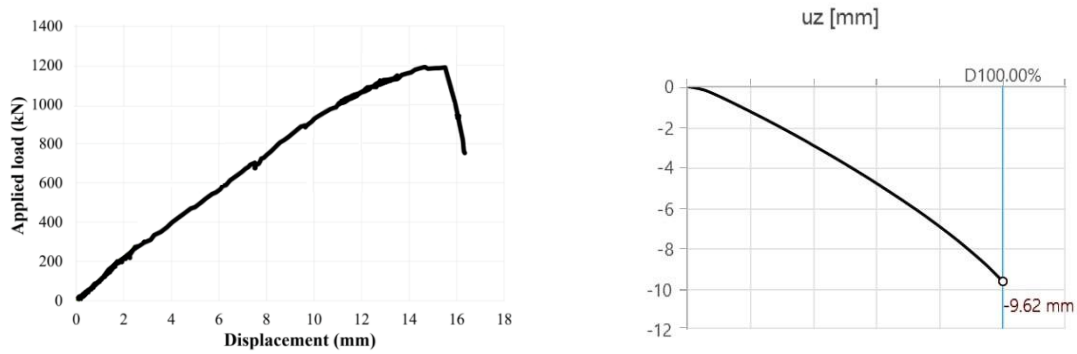


Fig. 6. Applied load vs. vertical displacement curve at $x = 173.2$ cm. a) tested specimen. b) IDEA StatiCa-Nonlinear.

Conclusion

IDEA StatiCa employs a topology optimization tool customized for D-region elements, significantly enhancing the design process through optimized material usage, improved structural performance, and effective reinforcement layouts. The model effectively predicted the structural capacity of a deep beam, with a maximum load estimation of 1045.3 kN closely aligning with the experimental result of 1191 kN, demonstrating the effectiveness and safety of its conservative prediction approach. Additionally, the development of cracks during the specimen's failure aligned with the stress flow predictions made by IDEA StatiCa, further validating the model's accuracy. This stress flow analysis also supports the development of a Strut-and-Tie approach, providing a robust and reliable framework for analyzing and designing structural elements.

The deflection behavior predicted by IDEA StatiCa demonstrated close correspondence with the experimentally measured deflection, underscoring the software's capability to simulate real-world structural responses accurately. Nonetheless, the deflections computed by IDEA StatiCa were consistently lower than those observed experimentally, indicating that the software employs a conservative approach to estimating deflection behavior.

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