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Beyond The Standards: Analyzing Rc Deep Beam Design Codes

Jyothis S[1], Jayasree S[2]

[1]PG Student, Department of Civil Engineering, Mar Baselios College of Engineering and Technology, Trivandrum, Kerala, India
[2]Professor, Department of Civil Engineering, Mar Baselios College of Engineering and Technology, Trivandrum, Kerala, India

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Abstract - *The behavior of reinforced concrete (RC) deep beams is intricate and crucial for structural design and safety. This study aims to conduct a comparative analysis of the strength and behavior of RC deep beams designed according to the Indian Standard IS 456 (2000) and the American Concrete Institute (ACI) 318 (2019) codes through experimental investigation. Six specimens, three designed under each code, were prepared using M30 grade concrete and subjected to three- point loading to assess load-deflection response, crack width, and strain distribution. Additionally, the shear strength and load-deflection response were compared with results obtained using the strut and tie model based on the ACI 318 (2019) code. The study aims to ascertain the efficacy of different design approaches in predicting the strength of RC deep beams by comparing experimental findings with existing strength prediction models. The specimens, reinforced with steel bars as per IS 456 (2000) and ACI 318 (2019) codes, were tested, with the ACI 318 model exhibiting superior shear strength prediction. Results indicated that the ACI 318-designed beams displayed 25.7% higher ultimate load capacity compared to those designed using IS 456. Moreover, ACI 318-designed beams exhibited enhanced flexural parameters such as ultimate capacity, deflection, and ductility, surpassing IS 456-designed beams by 25-35%. Utilizing the strut and tie model for deep beam reinforcement design improved flexural behavior, resulting in lower crack widths and higher energy absorption capacities. Overall, the study concludes that ACI 318-designed models outperform IS 456-designed models in terms of strength and behavior of RC deep beams, highlighting the effectiveness of the ACI 318 approach in structural design.*

Key Words: Deep beams, Reinforced concrete, crack width, IS 456, ACI 318, strut-and-tie modeling

1.INTRODUCTION

Infrastructure initiatives within countries have greatly benefited from Reinforced Concrete (RC) constructions, playing a pivotal role in advancing economic growth [1]. Ensuring the long-term survival of these structures are crucial for promoting economic growth, critical to a nation's functioning and developmentt. Deep beams are commonly used in the design of pile-supported foundations, transfer girders for tall buildings, and bending caps for bridges [2]. As per IS 456(2000) deep beams structural elements where effective span-to-height ratio is less than or equal to 2 for simply supported, or if they are continuous beams with a ratio less than or equal to 2.5[3].

In contemporary construction practices, RC deep beams provide enhanced structural performance and load-carrying capacity, making them suitable for supporting heavy loads over large spans [4]. In deep beams there is a deviation from linearity in the strain distribution and shear deformations become considerably larger than the flexural effects. Since deformation predominates in the behavior of deep beams, the conventional assumptions made about plane sections in normal beam analysis are no longer sufficient. As a result, a design strategy focused on the failure mechanisms unique to deep beams is required [5].

Due to their small span-to-depth or shear span-to-depth ratio, stress trajectories in deep beams are disrupted, rendering conventional simple beam design procedures inapplicable. ACI 318(2019) incorporates more advanced analytical methods and experimental data to provide safer and more efficient designs for deep beams [6].

Different design codes provide guidelines and methodologies for the design of deep beams, each with its own approach and criteria. Two prominent design codes for deep beams are IS 456 (2000) and ACI 318 (2019) [3], [7]. This code addresses various aspects of deep beam design, including flexural, shear and axial forces, as well as detailing requirements for reinforcement. Additionally, ACI 318 (2019) introduces the concept of the strut and tie model (STM), a versatile design tool recommended for addressing complex stress distributions in deep beams [7]. The beams that belong to the deep member category are distinguished by the fact that compressive stresses are directly transmitted from the loading to supporting points (struts), whose ends meet with tensile stresses (ties) at particular points (nodes) to create the appearance of a truss [8]. In experimental investigations the deep beams with reinforcement strut higher than control deep beam with IS 456 (2000) reinforcement and with less displacement [9].

Deep beams consist of two regions as the B- region and D-region. In the B-region, linear strain distribution simplifies analysis and design based on flexural theory. Conversely, the D-region involves discontinuities such as openings, alterations in geometry, concentrated loads, and shear forces. These complexities, including intricate strain changes and large concentrations of stress trajectories, necessitate a more advanced method of analysis and design for deep beams in the D-region [10].

In order to ensure the structural integrity and safety of deep beam elements, IS 456 (2000) offers guidelines for reinforcement detailing, such as bar sizes, spacing, and detailing requirements. However, the significance of D-region, which is crucial for the design of deep beam to be used as a structural element in infrastructures, is not specified. The American Concrete Institute ACI 318-14 code defines deep beams as "Structural Members loaded on one face and supported on the opposite face such that struts-like compression elements can develop between the loads and the supports and that satisfy either a) Clear-span does not exceed four times the overall member depth or b) Concentrated loads exist within a distance of 2h from the face of the support", whereas the ACI code specifies the design of D-region using strut and tie method [11].

2. RESEARCH SIGNIFICANCE

A study is crucial for bridging the existing gap in knowledge regarding the efficiency of different design codes in predicting and optimizing the load-bearing capacity of deep beams. Additionally, insights into the structural performance, ductility, and failure mechanisms of deep beams under varying loading conditions are essential for advancing design standards and practices within the realm of reinforced concrete construction. Present study aims to fill this research gap by conducting a comprehensive comparative analysis between RC deep beams designed under IS 456(2000) and ACI 318(2019), providing valuable insights for structural engineers and designers. Deep beams play a vital role in the infrastructure such as bridges, flyover, pile foundation etc. and the construction of service lines along these structures are considered to be uneconomical and time consuming. Therefore, the openings in deep beams are provided to carry these service lines and the design for these opening can be done using strut and tie method only as per ACI Code. Hence it is necessary to conduct an experimental investigation analyze the structural performance capacity of both type of deep beams designed using ACI 318(2019) and IS 456(2000) codes.

3. EXPERIMENTAL PROGRAM

3.1Material Properties and Mix Proportion

Materials and mix obtained in this investigation suitable for M30 grade concrete which is generally used in RC deep beam structures. Portland Pozzolana cement, manufactured sand passing through 4.75 mm sieve size, serves as the fine aggregate and conforming to zone 11 of IS 383-1970(reaffirmed 2002), crushed granite, with aggregate sizes of 20 mm, is utilized as the coarse aggregate. The mix proportion obtained was of the ratio 1:1.88:3.27 with a water cement ratio of 0.45 and the mix design was done as per IS10262(2019).

3.2 Flexural behavior of RC Deep beams

3.2.1 Specimen Details

The deep beam specimen was prepared according to the reinforcement arrangement specified in both IS 456:2000 and ACI 318:2019. Six reduced-scale RC deep beams were prepared in this study. The size of the specimen taken 200 x 650 x 1000 mm. Three deep beams were prepared in accordance with design code IS 456:(2000), denoted by IS as illustrated in Figure 1, and three deep beams as the STM in accordance with ACI 318:(2019), denoted by ACI as illustrated in Figure 2.

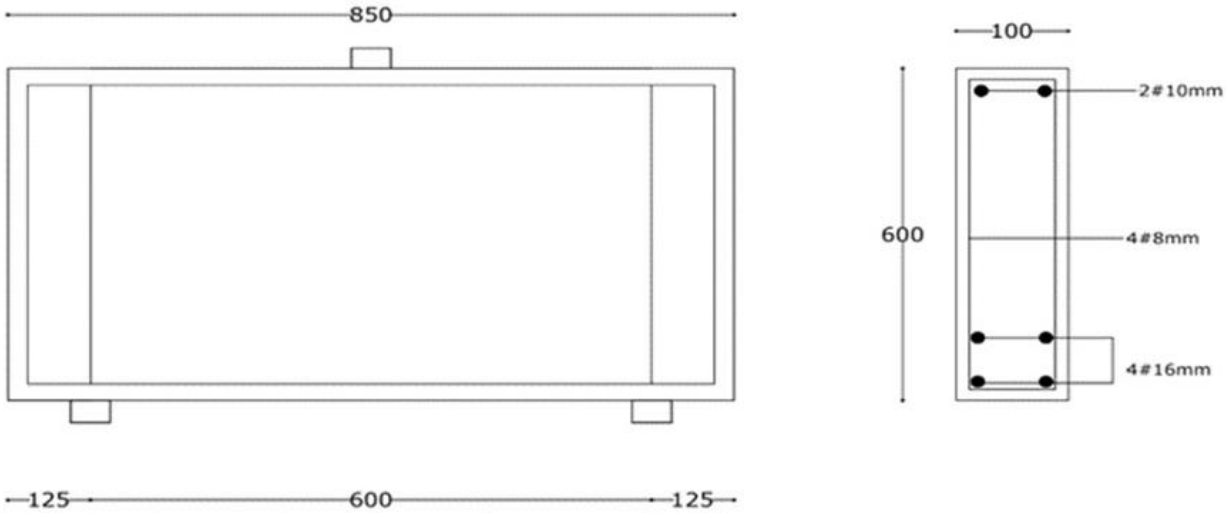

Fig -1: Specimen Size and Reinforcement Diagram IS

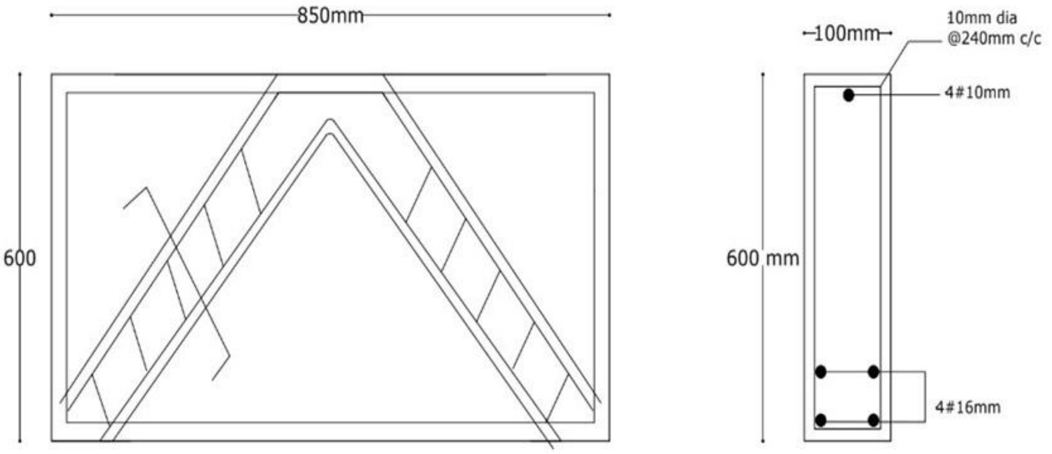

Fig-2: Specimen Size and Reinforcement Diagram ACI

The reinforcement ratio (p), for all specimens was 1.14%. The main steel bars in the IS designated beams are of diameter 16 mm, while those in the ACI designated beams having diameter of 12 mm. These parameters ensure consistency and comparability among the test specimens, facilitating a comprehensive analysis of their behavior and performance.

Strain gauges were affixed to the top and bottom steel reinforcement inside for specimens designated as IS, while for specimens designated according to ACI, two strain gauges were attached to the strut portion and one to the bottom steel reinforcement. The mould setup, along with the reinforcement, is depicted in Figure 3. Vibration was given to the concrete while preparing without disturbing the strain gauges. After 24 hours of casting, the specimens were demoulded and placed in a curing tank for 28 days, covered with jute sacks for protection.

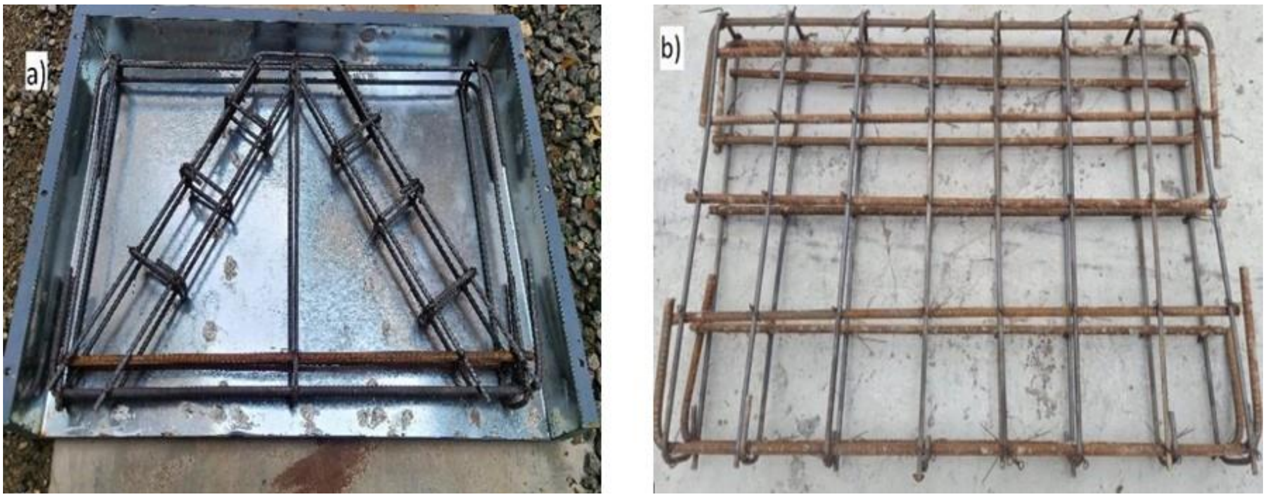

Fig-3: Reinforcement detailing of specimens a) ACI b) IS

3.2.2 Test Setup

The strain in the concrete was monitored with Linear Variable Differential Transformers (LVDTs) were fixed to the top and bottom front faces of the beam. An LVDT was also installed at the bottom mid-span to record beam deflection in relation to applied loads. Companion cubes, which were cast next to the concrete deep beam specimens and tested on the testing day as well, were used to check the average compressive strength of the concrete matrix.

The test setup, shown in Figure 4, features one hinged support and another side with a roller support. To prevent the crushing of the support base during loading, a cut piece of rubber tyre is placed above the steel supports, with a jute sack layered on top. This arrangement ensures uniform distribution of applied load and reaction forces on both the top and bottom surfaces of the beams. The load was applied on the centre of rectangular 100x100 steel plates.

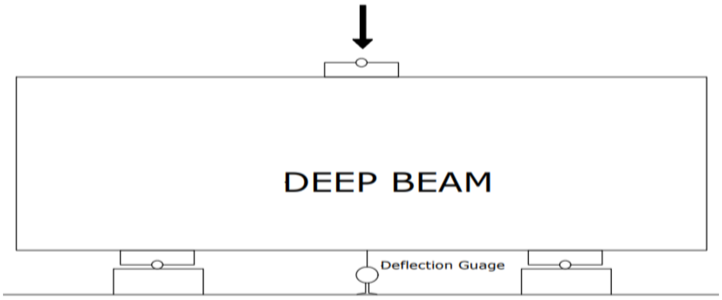

Fig-4: Schematic Diagram of Loading Device

3.3 Testing

Test setup shown in Figure 5, a 1000 kN Universal Testing Machine (UTM) was used and central load was applied for all specimens. In order to precisely measure beam deflection, dial gauges with a minimum count of 0.01 mm are mounted beneath each beam at the mid-span. The steel frame, which is positioned to apply one-point loading to the beam specimen, receive the force applied by the hydraulic cylinder at its center. Throughout the testing process, accurate and regulated loading conditions were ensured by the depicted configuration, which demonstrates a steady application of weights at intervals of 10 KN. The width of crack was measured using a crack detecting microscope of 50x magnification.

Fig-5: Test setup

4. RESULTS AND DISCUSSIONS

4.1 Crack pattern and Crack propagation

Two types of cracks were identified initially: flexural cracks and shear cracks. Flexural cracks originating from the bottom of the specimen and extending vertically towards the neutral axis of the beam. The shear cracks, which manifest as diagonal fissures in the shear span of the beam were propagated towards the center span. Prior to failure, the responses of all specimens were consistent. When the load was applied noticeable concrete crushing at the supports were noted. Diagonal cracks observed were developed at the bottom of the beam as the load reached to 40–50% of its maximum load. After that, these cracks were propagated in the direction of the main strut, and then towards the inner edge of the support. Simultaneously, diagonal fissures widened in the shear span center as they stretched along the beam. Eventually, a brittle mode that was identified as diagonal splitting from the support to the loading point was found responsible for the failure of every specimen. Figure 6 shows the crack pattern at various load stages, and the same was consistently noted for all specimens.


(a) ACI 318:2019
(b) IS 456:2000

Fig-6: Diagonal Splitting Failure in The Beam

4.2 Crack Width

IS and ACI specimen exhibit significant variations in the load vs crack width plot as shown in Figure 7. Initially the crack width is almost same for both IS and ACI specimens, afterwards IS specimen shows greater observed crack width which may be due to the STM implementation successfully mitigates fracture formation and prevents further crack propagation.

While limited crack formation is acceptable in deep beams, the crack widths in IS beams just barely exceeded over acceptable bounds, while beams developed in accordance with STM stayed within acceptable bounds. Notably, near the bottom of the beams, fracture widths were more noticeable in the direction of the excessive tension side in ACI specimen.

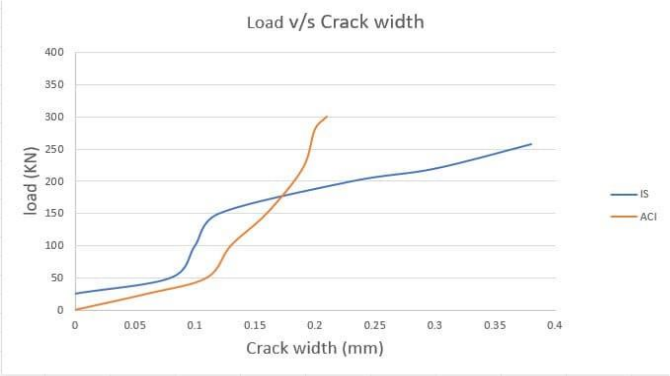

Fig-7: Load vs crack width for deep beam specimens

4.3 Load Deflection Plot

The Load vs Midspan Deflection curve illustrates the relationship between applied load and midspan deflection for the tested specimens. In both cases as the load increases, the midspan deflection increases, which can be noted from Figure 8.

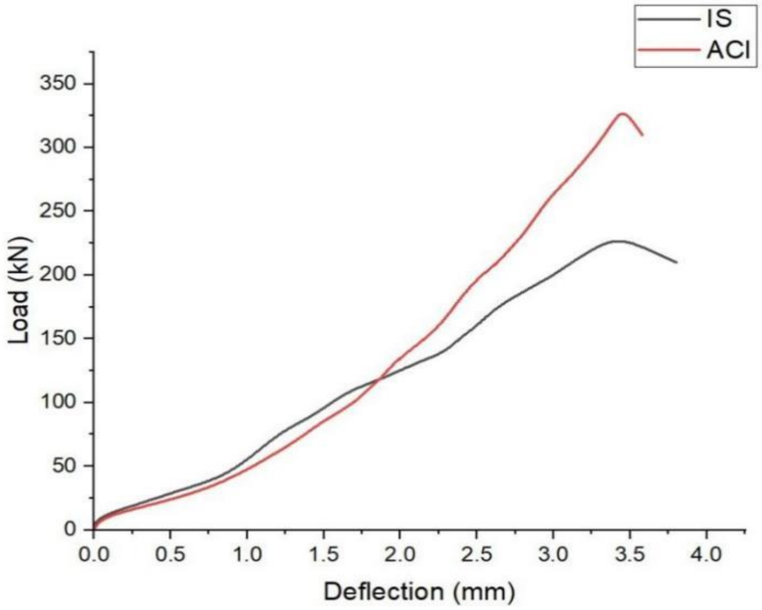

Fig-8: Load Vs Midspan Deflection Curve of Tested Specimens

Midspan deflection corresponding to ultimate load are noted the loading process of each specimen, a predominant linear relationship between load and displacement was observed initially, indicating elastic behavior. However, as loading progresses, the load-versus-displacement curve transitions into a nonlinear phase, signifying the onset of plastic deformation and yielding within the material. The occurrence of the first crack load and the ultimate load of the specimens was calculated, with results indicating that the ACI specimens demonstrate notably higher ultimate strength compared to those designed according to IS.

The initial crack load, ultimate load and energy absorption capacity of the specimens were calculated and tabulated in Table 1. These values offer insights into the structural performance and resilience of each beam design, aiding in the comparative analysis of their effectiveness in withstanding applied loads.

Table -1: Initial Crack Load, Ultimate Load, Yield load and Energy Absorption of Specimens

Specimen Name	First Crack Load (kN)	Yield Load (kN)	Ultimate Load (kN)	Energy Absorption (KNmm)
IS	106	270	256	455.81
ACI	156	353	338	480.8

These values offer insights into the structural performance and resilience of each beam design, aiding in the comparative analysis of their effectiveness in withstanding applied loads.

4.4 Moment Curvature Relationship

The curvature of a beam is directly influenced by its deflection. Figure 9 illustrates the Moment Vs Curvature of the tested specimens, delineating three distinct stages. This graph provides crucial insights in designing beams to safely carry loads without failure, monitoring structural health, and advancing materials and structural designs.

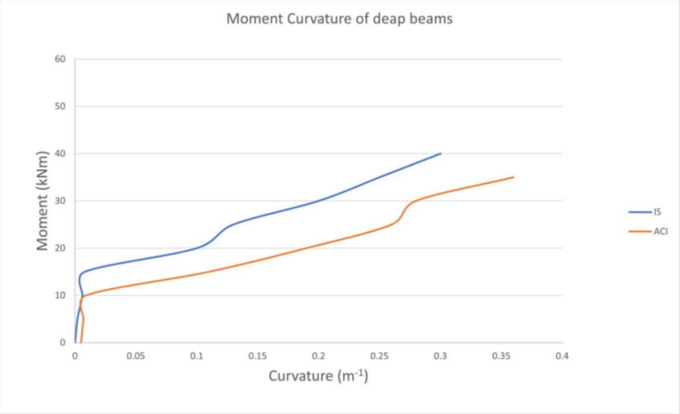

Fig-9: Moment Vs Curvature of Tested Specimens

It was observed that specimens designed according to ACI displayed greater curvature compared to those designed using IS. This difference in curvature suggests variations in the structural behavior of the beams under load. Specifically, ACI specimens exhibited a higher degree of eccentricity, leading to increased curvature values. This finding underscores the importance of considering design code specifications in predicting and understanding the behavior of reinforced concrete beams, particularly in terms of their deflection and curvature characteristics.

4.5 Ductility indices

The displacement ductility index values for the IS specimen calculated as 8.2, while the ACI specimen demonstrate a slightly higher value of 9.92. The results suggests that beams designed with the ACI code using the STM approach possess greater deformation capacity compared to those designed with IS. This observed difference in ductility can be attributed to the enhanced load carrying capacity of beams achieved through the application of the strut and tie method for reinforcement detailing. The strut and tie method offers a more refined and optimized approach to distributing loads within the beam, thereby improving its overall structural performance and ability to withstand deformation without failure. Consequently, the higher displacement ductility indices observed in the specimens designed with the ACI code indicate their enhanced ability to absorb energy and undergo larger deformations before reaching failure, highlighting the efficacy of the ACI approach in enhancing the ductility of RC deep beams.

5. CONCLUSIONS

The study conducted a comprehensive analysis of reinforced concrete (RC) deep beams designed according to the IS 456(2000) and ACI 318(2019) codes, focusing on various structural performances. Key observations revealed the presence of flexural and shear cracks, with diagonal splitting failure being the predominant mode. Crack width analysis showed that ACI beams had slightly narrower widths due to the reinforcement pattern specified by the strut-and-tie model (STM). Additionally, ACI-designed beams demonstrated a remarkable 25.7% higher ultimate load capacity and exhibited 25-35% higher flexural parameters compared to IS-designed beams. The energy absorption capacities of ACI beams were notably higher, as evidenced by their moment-curvature relationships and ductility indices, further emphasizing their superior performance. The use of STM in ACI-designed beams resulted in improved flexural behavior, characterized by lower crack widths and higher energy absorption capacities. These findings highlight the effectiveness of the ACI 318 (2019) code in enhancing the load-carrying capacity and structural performance of RC deep beams. Future research could explore the impact of various percentages of openings in RC deep beams, investigating how different opening configurations affect beam behavior and performance. This would provide valuable insights for structural engineers and designers, contributing to advancements in design codes and practices within the field of reinforced concrete construction.

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