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A Comprehensive Review of the Structural Behaviour and Design of Reinforced Concrete Dapped-End Beams

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ABSTRACT

This paper offers a thorough review of the behavior and design of non-prestressed reinforced concrete dapped-end beams (RC-DEBs). Often used in precast construction for their architectural and structural benefits, dapped ends feature geometric discontinuities interrupting the natural flow of internal stresses. Consequently, traditional design methods often struggle to accurately capture the complex stress patterns that develop in these areas. Based on experimental investigations from 1979 to 2024, the review emphasizes key factors like shear span-to-depth ratio (a/d), concrete compressive strength, hanger reinforcement arrangement, and detailing practices, all of which significantly affect structural performance. A common failure mode involves diagonal tension cracking at the re-entrant corner, especially in short-span DEBs where shear-compression interaction is predominant. The review examines various analytical models, such as the Strut-and-Tie Method (STM), To improve the design of shear-end beams, theories such as shear-friction theory and softened truss-based approaches provide powerful analytical frameworks. Strengthening methods using steel fiber-reinforced concrete and externally bonded CFRP sheets have demonstrated significant improvements in shear capacity and post-cracking ductility. The paper concludes with practical design recommendations, including the use of inclined reinforcement, ensuring sufficient anchorage detailing, and applying performance-based analysis to enhance accuracy and safety. Finally, the paper outlines paths for future studies, highlighting the importance of developing nonlinear modeling and hybrid retrofitting strategies specifically designed for disturbed regions in dapped-end beams.

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1. Introduction

Precast concrete structural systems have seen a significant increase in popularity recently, and the reason behind this is clear: They offer high efficiency, faster construction times, and better quality control.One of the key components of these systems is the dapped-end beam (DEB). You'll find these beams widely used in parking garages, bridge decks, and precast floor systems. The main function of these beams is to reduce the overall structural depth, allowing the use of simpler support connections without the need to increase the story height. (Lu et al., 2015; Aswin et al., 2015) [1,2].

However, the sudden geometric change at the dapped-end region interrupts the natural flow of internal stresses, creating disturbed areas (D-regions) with high stresses at the re-entrant corner and nib (Desnerck et al., 2016) [3]. Without proper reinforcement, these zones are prone to early cracking, diagonal shear failure, and brittle collapse (Wang et al., 2005; Yang et al., 2011) [4,5]. Classical flexural theory does not adequately address these zones; therefore, two primary design methods have been developed: the Strut-and-Tie Model (STM), which views the D-region as a truss with compressive struts and tensile ties (ACI 318-19; Lu et al., 2015) [6,1], and the Shear-Friction Model, originally introduced by Mattock and Chan (1979) [7], which treats the re-entrant corner as a friction interface resisted by hanger reinforcement.Recent innovations have incorporated high-performance materials such as fibre-reinforced concrete (FRC) Mohamed & Elliott (2008) [8], steel fibres Peng (2009) [9], and carbon fibre-reinforced polymers (CFRP) Shakir et al. (2018) [10] to enhance post-cracking ductility and shear capacity. Experimental studies show that key factors--including the shear span-to-depth ratio (a/d), concrete compressive strength, reinforcement arrangement, and anchorage conditions play a crucial role in determining the failure modes and load capacity of DEBs Lu et al. (2012); Ahmad et al. (2013); Desnerck et al. (2018) [11; 12; 13].Various analytical models have also been proposed to predict the shear behavior of dapped-end beams better. These include modified STM formulations Lu et al. (2015) [1], energy-based failure mechanics Yang et al. (2011) [5], and hybrid truss models Wang et al. (2005) [4]. Still, there are discrepancies among predictions from different design codes (ACI 318-19; Eurocode 2; PCI 1999) [6; 14; 15], especially for cases involving short shear spans and atypical reinforcement setups Aswin et al. (2014) [16].

This paper provides a comprehensive review of the current understanding of the structural behavior, failure mechanisms, and design strategies for non-prestressed reinforced concrete dapped-end beams. It highlights experimental and analytical advances to identify key design issues, evaluate reinforcement options, and guide future research and practical design improvements.

2. Experimental Investigations and Observed Behavior

This section provides an overview of experimental studies conducted over the past four decades on the structural behavior of reinforced concrete beams with cut ends, commonly referred to as dapped-end beams (RC-DEBs). The selected research highlights the progressive development of knowledge in this field, emphasizing the key parameters and influencing factors that govern the performance and failure mechanisms of RC-DEBs.

2.1 Matock and Chan(1979) - Shear Friction Foundation

Mattock and Chan (1979) [7] introduced a foundational shear-friction model that has significantly influenced the design of dapped-end beams and other discontinuity regions in structural systems. This model proposes that shear transfer across cracked concrete interfaces is governed by friction mobilized through reinforcement that resists relative movement along the shear plane. The nominal shear strength is expressed as:

Vn=cAc+u As fy 1

Where: ***Vn*** is the nominal shear strength, cAccAc is the cohesion term accounting for chemical bond and aggregate interlock, μμ is the friction coefficient, ***As*** is the area of reinforcement intersecting the crack, and ***fy*** is the yield strength of this reinforcement.

This model was later adopted in ACI and PCI provisions, especially for cold joints, precast interfaces, and dapped ends, where relative sliding may occur due to concentrated loads or discontinuities in geometry. For validation, Mattock and Chan conducted full-scale tests on eight RC dapped-end specimens under vertical and combined loading, varying the shear span-to-depth ratio (α/dα/d) and hanger reinforcement. The key finding was:

*Cracking: Diagonal cracks occurred regularly at the re-entrant corner (the angle inside the web and nib) when the load reached around 20% of the ultimate capacity.

*Failure mode: The final failure was caused by diagonal tension failure in the strut and was marked by concrete spalling around the site where the load was applied, which showed localized crushing and loss of confinement.

•Design model: A shear-friction-based design method was suggested, and it has subsequently been added to the design rules of both the PCI (Precast/Prestressed Concrete Institute) and the ACI (American Concrete Institute), especially for deep areas where a/d<1.0$a/d<1.0$. Based on the experimental findings, a design-oriented formulation of the shear-friction model was proposed to more accurately account for the behavior of disturbed regions in precast and monolithic connections. The design expressions are as follows:

v u=V u/ϕ bd≤0.2 √f c′$vu=Vu/\phi bd\leq 0.2\sqrt{fc'}$.... (2)

$Avh=Vu/\phi fy$ …………………….… (3)

Where:

$v\ u$: nominal shear stress, V u: the shear force that has been considered,

ϕ: a The constructor that lowers strength, b the width that works

d: real depth, A v h: area of hanger reinforcement

f y: the strength of the hanger reinforcement when it breaks, f c′: the required compressive strength of concrete.

These equations are valid under the following conditions:

1. a/d<1.0, indicating deep beam behaviour:

The a/d ratio is the distance from the applied load to the nearest support (a) divided by the beam’s effective depth (d). When this ratio is less than 1.0, the beam no longer behaves like a typical flexural member. Instead, the load is transferred directly to the support through an inclined compression strut, a mechanism known as arching action. In this case, the assumption of linear strain distribution is not valid, and traditional flexural theory cannot be used. Therefore, models like the Strut-and-Tie Model (STM) are needed to analyze the structural behavior accurately.

2. The shear plane is either cracked or intentionally roughened:

The shear transfer surface is often either pre-cracked due to applied loads or intentionally roughened during casting, particularly at joints between precast elements or at critical interfaces such as between the web and flange of a beam. This surface roughness enhances the mechanical interlock and friction between concrete faces, improving the beam’s shear resistance through shear-friction mechanisms.

3. A sufficient clamping force is present, such as from axial loads or self-weight: For the shear-friction mechanism to function properly, a vertical compressive force must act on the shear plane to prevent sliding between the concrete surfaces. This clamping force enables the transfer of shear through friction and mechanical interlock. It can originate from various sources, such as the self-weight of the structural element, an axial load or tensile force generated by the bonding system or internal reinforcement, or compressive stresses caused by post-tensioning (prestressing). These forces are vital for activating the shear-friction mechanism and enhancing the member's structural integrity.

4. Reinforcement is adequately anchored and expected to yield before brittle failure occurs:

Adequate reinforcement, such as U-bars, stirrups, or inclined bars, must cross the shear plane to ensure effective shear transfer through friction. This reinforcement must be adequately anchored to prevent slippage or premature pull-out before yielding. Its primary function is to resist the shear forces transmitted through friction and mechanical interlock. Since brittle failure, such as sudden concrete cracking or spalling, is undesirable, the reinforcement is designed to yield first, providing a more ductile and predictable failure mode that enhances structural safety.

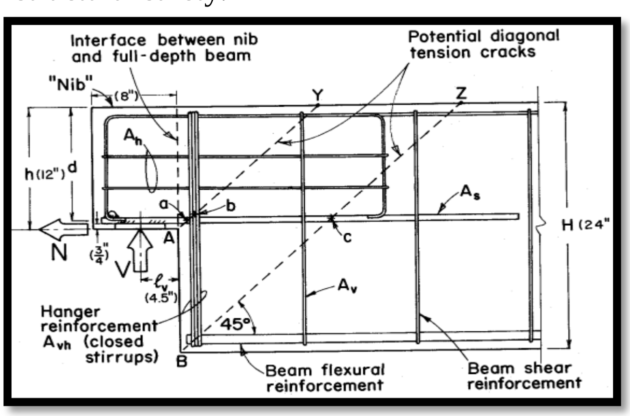


Figure (1) Mattock and Chan (1979) "Typical dapped-end reinforcement and location of potential diagonal tension cracks.
Note that the dimensions in parentheses are those of the test specimens"

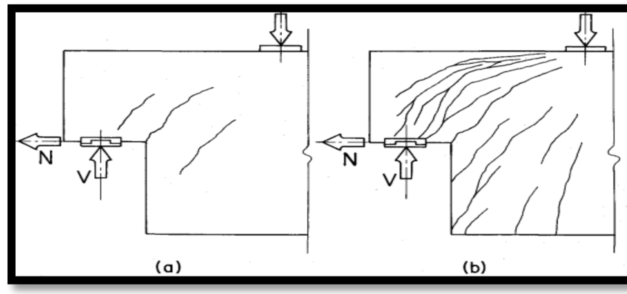


Figure (2) Mattock and Chan (1979) "Typical cracking patterns of dapped-end beams tested: (a) at service load and (b) before fail"

Figures (1) and (2) from Mattock and Chan's (1979) seminal study illustrate typical reinforcement detailing in dapped-end beams and the progression of cracking under applied loads.Figure1presents the typical reinforcement layout and identifies the critical zones where diagonal tension cracking is likely to initiate, notably near the re-entrant corner.

Figure 2 contrasts the cracking patterns observed at service load levels and just before failure, clearly showing how cracks propagate diagonally from the nib region toward the beam body, following the strut direction.

Despite the utility and simplicity of the shear-friction model in design applications, it possesses several limitations. Most notably, it does not adequately capture the multi-axial stress states, principal stress rotations, or concrete softening behavior commonly found in disturbed regions (D-regions) such as dapped ends. To address these shortcomings, Vecchio and Collins (1986) [17] developed the Modified Compression Field Theory (MCFT), a nonlinear, mechanics-based model that provides a more comprehensive understanding of cracked reinforced concrete behavior. Unlike the shear-friction approach, which treats shear transfer through aggregate interlock and reinforcement slip, MCFT models the interaction of shear and everyday stresses across the entire cracked web by incorporating effects such as tension stiffening, compression softening, and variable principal stress orientations. This allows for a more realistic representation of stress distribution and crack development in regions with complex geometries and load paths. MCFT has since become a cornerstone in advanced structural analysis, underpinning modern design codes (e.g., CSA A23.3, AASHTO LRFD) and nonlinear finite element analysis (FEA) tools used for evaluating shear-critical elements such as RC dapped-end beams, deep beams, and corbels. Its adoption has enhanced the safety and accuracy of predictions related to shear capacity and failure mechanisms, particularly in cases involving combined loads or irregular stress trajectories.

2.2. Liem (1983) Inclined Reinforcement as an Alternative to Hangers

Liem (1983) [18] conducted one of the earliest systematic investigations into the use of inclined reinforcement as an alternative to conventional horizontal hanger bars in reinforced concrete dapped-end beams (DEBs). His hypothesis was rooted in the observation that diagonal tension cracks typically initiate at the re-entrant corner, particularly in members with low shear span-to-depth ratios (a/d < 1.0), where arching action and deep beam behavior dominate. In an experimental program involving eight full-scale beams, Liem compared the performance of specimens reinforced with traditional horizontal hangers to those fitted with inclined bars at 45°. The results showed that inclined reinforcement increased the shear capacity by up to 60%, despite requiring approximately 41% more steel area. In some cases, shear strength was quadrupled. This enhancement was attributed to the superior alignment of inclined bars with the principal diagonal tension field, enabling more effective crack bridging and internal force redistribution. Theoretically, Liem's approach aligns closely with the Strut-and-Tie Model (STM), where inclined reinforcement acts as the tension tie crossing the diagonal crack path. When a concentrated load is applied near the dapped end, a concrete strut (c) develops diagonally from the load to the support, and tensile stresses perpendicular to this strut require reinforcement in the form of ties (a). Inclined bars, positioned along these stress trajectories, directly resist these tensile forces, whereas horizontal hangers intersect the crack path inefficiently and contribute less to tension control.

$$V u = 0.7\ \phi\sqrt{f\ c'}\ b\ h \qquad \ldots\ldots\ldots\ldots\ldots\ldots 4$$

Where: V u: the shear capacity

ϕ: factor for lowering strength

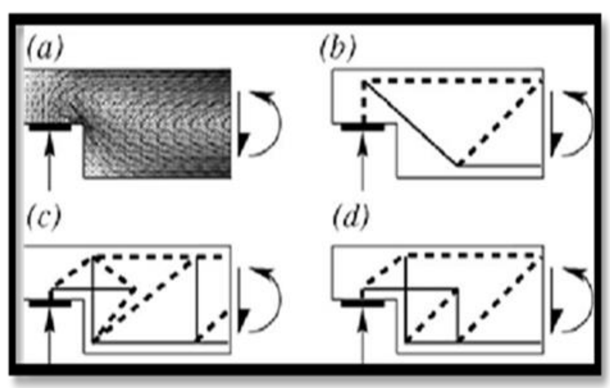
f c ′: the concrete's stated compressive strength

b: the breadth of the segment

h: the nib's total height.

As shown in Figure 3, adapted from Fernández Ruiz and Muttoni (2007) [19], the functional role of inclined reinforcement in STM is clarified:

(a) shows the elastic stress field prior to cracking,(b) presents an STM where the inclined bar acts as the main tie,(c), and (d) reflect standard reinforcement practices.



Figure(3) Adapted from Miguel Fernández Ruiz and Aurelio Muttoni (2007)(26)

"Dapped-end beam: (a) linear elastic (uncracked) stress field; (b) possible truss model inspired in elastic stress field; and (c) and (d) truss models corresponding to usual reinforcement layouts".

Fernández Ruiz and Muttoni(2007) [26] emphasized that reinforcement detailing in disturbed regions (D-regions) must follow the natural trajectories of internal stresses. The stress paths observed in Figure 3 validate the use of inclined reinforcement as a direct mechanical response to diagonal tension, aligning structural detailing with physically realistic stress fields.

Thus, Liem's study, supported by experimental evidence and theoretical modeling, demonstrates that inclined reinforcement is not merely an alternative to hanger bars but a key structural strategy for achieving improved crack control, ductility, and ultimate shear resistance in reinforced concrete dapped-end beams.

2.3. Wang et al. (2005): Bent bars and the truss mechanism

Wang et al. (2005)[4] conducted a thorough parametric study to examine the shear behavior of reinforced concrete dapped-end beams (RC-DEBs), focusing on the combined effects of bent bars, vertical stirrups, and dap depth within a refined truss mechanism. Their experimental program tested 24 full-scale specimens under vertical load, enabling systematic evaluation of reinforcement arrangements in disturbed regions. Initial cracking in the specimens appeared at 40° and 60° relative to the horizontal axis, closely matching the predicted paths of diagonal tensile stresses. Ultimate failure generally resulted from a shear-compression mechanism, marked by concrete crushing near the re-entrant corner and a decline in the capacity of the compression zone. Using bent bars aligned along expected crack paths proved particularly advantageous, boosting post-cracking stiffness and shear capacity by intercepting and restraining diagonal cracks, enhancing ductility, and delaying brittle failure. Wang et al. developed a truss-based shear model to quantify the individual contributions of each component.

$$V_u = V_c + V_s + V_b = \alpha f_c' bd + \beta A_s f_y + \gamma A_b f_y \sin(\theta) \quad \ldots\ldots\ldots\ldots 5$$

Where:

V_u: ultimate shear capacity, f_c': concrete's compressive strength

, b: beam width, d: adequate depth, A_s: area of vertical stirrups,

A_b: the region of bent bars, f_y: yield strength of reinforcement,

θ: bent bars' angle to the horizontal,

$\alpha = 0.0546$, $\beta = 0.8583$, $\gamma = 1.0$

This model improves upon earlier shear-friction-based approaches, such as those proposed by Mattock and Chan (1979)[7], by explicitly integrating the geometry and directionality of reinforcement into the design. Whereas traditional models emphasize sliding along crack planes and cohesion-friction mechanics, Wang's approach is grounded in truss-like internal force transfer, providing a mechanically consistent and less conservative estimate of shear strength. Ultimately, this method proved remarkably accurate for short-span beams with complex reinforcement layouts, validating the role of bent bars as an effective and necessary component in shear-critical regions. It is thus well-suited to performance-based design philosophies that require detailed force modeling in disturbed regions.

2.4 Lu et al. (2003, 2012, 2015): Refined STM and High-Strength Concrete

Over the span of more than a decade, Lu et al. (2003, 2012, 2015) [20,11,1] carried out an extensive program of experimental and analytical research to enhance the predictive capabilities of the Strut-and-Tie Model (STM) for reinforced concrete dapped-end beams (DEBs) constructed with high-strength concrete (compressive strength reaching up to 69 MPa). Their research aimed to establish a unified framework that could accurately describe the behavior of DEBs not only in deep beam conditions (a/d < 1.0) but also in transitional zones (a/d ≈ 1.0–2.0), where conventional flexural theory is no longer valid. In their 2003 study [20], the team experimentally investigated DEBs with shear span-to-depth ratios around 1.0 and noted that diagonal cracking at the re-entrant corner was the prevalent failure mode, driven primarily by shear-compression interaction. Although higher concrete strength led to greater load capacity, the gains diminished at elevated strengths due to concrete softening and the degradation of strut integrity.

To overcome these nonlinear effects, Lu et al. (2012) [11] introduced a refined STM that integrates reduction factors to account for strut softening (γh) and reduced tie effectiveness, particularly in high-strength concrete systems where brittle failure is a growing concern. Their modifications were calibrated to remain consistent with safety requirements prescribed in major design codes.

$$Vu = Rd \times f'c \times Astrut + Rh \times Atie \times fy \quad \text{……….6}$$

Where:

Vu: ultimate shear resistance, **fc′**: compressive strength of concrete, A strut is the effective cross-sectional area of the concrete strut, A tie: represents the area of tie reinforcement (typically hanger bars), and **fy**: is the yield strength of the steel reinforcement

Rd = 1−γ The reduction factor,h, accounts for strut degradation,The empirical degradation parameters $0<\gamma h<1$.

This expression applies particularly to dapped-end beams with small shear span-to-depth ratios (a/d ≈ 1.0) in which shear-compression interaction prevails. Failure usually occurs as diagonal cracking at the re-entrant corner. With the increasing a/d ratio, the stress flow transitions to a flexure shear-bending behaviour. However, the disturbed region at the nib is critical and cannot be analyzed only based on classical beam theory. Also, although higher f′c increases the shear strength, there is a practical limit above which not only no more gain in the shear resistance, but also the high-strength concrete becomes brittle (conversely with the minimal leverage with the shear strength). Such a design approach strikes a balance between usability and performance, while also enhancing the reliability of the design as compared to the traditional code-based or empirical design methods. Indeed, it is a powerful analysis tool for designers, particularly with challenging support conditions and areas of geometric discontinuity.

2.5 Steel Fiber Self-Compacting Concrete by Mohamed & Elliott (2008)

In order to interpret the structural enhancements observed in the experimental program, Mohamed and Elliott (2008)[8] proposed a refined analytical model based on the softened strut-and-tie method (STM). This model was developed to capture concrete degradation under compression and steel fibers' tensile contribution. Specifically, it incorporated two major components: a softened strut that reflects the reduced strength of cracked concrete, and an additional empirical term representing the influence of fibers in bridging cracks and enhancing post-cracking tensile resistance.

The total shear capacity of the dapped-end region was defined using the following expression:

$$VDC = 0.81K \times \zeta \times fcu \times as \times bs \times \sin\theta + (\text{fiberterm}) \quad \text{.....7}$$

Where: **fcu** refers to the cube compressive strength of the concrete, **K** and **ζ** are empirical coefficients accounting for the geometry and softening of the material, as and bs denote the practical dimensions of the strut, **θ** is the angle of inclination of the strut relative to the horizontal, and **The fiber term captures** the additional shear resistance resulting from the crack-bridging capacity of steel fibers.

The model was helpful, especially for the dapped-end beam analysis, as it develops complex stress fields around the nib and re-entrant corner. Accurate modeling is critical due to concentrated moments and reinforcement congestion.Self-compacting concrete (SCC) improved constructability by allowing for the immediate avoidance of vibration, leading to better fiber distribution throughout the matrix. The uniform distribution of fibers was instrumental in bridging micro-cracks to delay the appearance of visible cracking. Experimental results confirmed the analytical predictions. The beams with 1% steel fibers provided complete performance, such as a delay in crack initiation compared to the FRC beams, a 20–25% increase in ultimate load carrying capacity, and an improvement in energy absorption and ductility of 20–50% after cracking. Such improvements were mainly related to a better confinement, a more efficient stress redistribution, and a controlled failure mechanism in the disturbed zone.

2.6 Anchorage Effects in Dapped Ends by Peng (2009)[9]

In a 2009 experimental investigation, Peng examined the influence of different anchorage detailing methods and hanger reinforcement placement on the behavior of reinforced concrete dapped-end beams (RC-DEBs) made with normal-strength concrete (f′ c= 33 MPa) and a shear span-to-depth ratio (a/d) of 1.0. Six full-scale specimens were subjected to monotonic four-point bending to isolate the structural response under service-type loading. Three anchorage techniques were evaluated: standard 90° hooked bars (Ø16 mm with 12d hook length), extended straight bars (24d development length), and mechanical anchorage systems using headed bars. The results demonstrated that proper anchorage significantly enhanced shear resistance and ductility, especially in specimens where hanger bars were placed close to the re-entrant corner and terminated with hooks or mechanical heads. The maximum shear capacity increased from 245 kN in beams with straight bars to 352 kN and 354 kN for beams with hooked and mechanically anchored bars, respectively, representing an increase of up to 44%. Additionally, the first diagonal crack was delayed by approximately 18% in load compared to poorly anchored specimens. Improved anchorage also reduced initial crack width, with values below 0.25 mm up to 75% of peak load (Pu), indicating enhanced confinement and better load transfer near the nib-support interface. Regarding deformation behavior, the ductility index, defined as the ratio of ultimate deflection to yielding deflection ($\Delta u/\Delta y$), increased from 1.7 in the control beam to 2.4 in beams with hooked or headed bar anchorage. Failure modes in poorly anchored specimens were brittle and characterized by sudden diagonal shear cracking at the re-entrant corner. In contrast, properly anchored beams exhibited more stable crack propagation and progressive failure.

These findings underscore the critical role of anchorage detailing in disturbed regions of RC-DEBs, where high stress concentrations develop. Ensuring adequate development length or mechanical anchorage in hanger bars enhances load path continuity, promotes ductile failure, and improves the safety margin. The study supports mechanical anchorage or hooked ends per ACI 318-25 provisions for anchorage within D-regions of deep or dapped-end beams..

2.7 Desnerck et al. (2016, 2018)[3,13]: Explicit Sensitivity and STM Assessment

Desnerck et al. Results of Two Experimental Studies on the Influence of Failure Modes in

Dapped-End Reinforcement detailing affects beams. Full-scale and half-joint specimens were considered with realistic loading conditions and specific reinforcement elements, as diagonal bars, hanger bars, and nib steel, that were incrementally cut or deleted to create subpar construction practices. Until the deck's collapse, diagonal reinforcement led to a loss of load capacity by as much as 39%. The beams with less hanger or nib reinforcement failed earlier, with an aggressive failure mode, emphasizing their structural sensitivity introduced by inadequate detailing. A comparative analytical method of a strut-and-tie model (STM) was used. Tool. The STM was structurally safe in its predictions but always erred on the side of under-predicting the load. Reflecting the inherently conservative nature of its carrying capacity. Failures are mainly caused by what was predicted, a lack of enough anchorage, or steel yield. These findings confirm that STM is a safe design practice, albeit a conservative one, and

2.8 CFRP Strengthening for DEBs by Shakir et al. (2018)[10]

Shakir et al. The capabilities of the carbon fiber reinforced polymer (CFRP) sheets used in the retrofitting of the reinforced concrete dapped-end beam (DEB) were analyzed [Trasca et al. The 14 specimens used for the experimental program were purposely designed with less internal steel reinforcement at either the nib or the hanger bars. Such a setup was designed to emulate the usual lack of reinforcement observed in real-world scenarios. In order to remedy these shortcomings, the researchers utilized externally applied CFRP strengthening schemes in various ways. The outcomes were positive: retrofitted beams utilizing CFRP markedly improved structural capability. Indeed, the ultimate load capacity increased by 20% to 30%, especially in beams with very little internal reinforcement. Based on the geometry and detailing of each specimen, the CFRP was installed in different configurations. The predominant one is a U-shape wrapping around the nib, which can effectively confine the core and thus increase the core shear resistance. In addition, there were configurations of fully wrapped jackets and side-bonded laminates, and the number of layers varied from one to three. As expected, adding several CFRP layers provided more confinement properties and controlled crack propagation. However, the failure modes of the strengthened beams varied. In certain instances, premature debonding occurred at the CFRP–concrete interface, particularly at sharp re-entrant corners of peak stress concentration. Failure of CFRP was either rupture or delamination, and it occurred in specimens where the anchorage or surface preparation was insufficient. Nevertheless, there was a significant enhancement in general behaviour: CFRP delayed the brittle shear failure, mitigated concrete spalling, and induced a more ductile progressive cracking pattern. The same results further confirm the contributory behavior of CFRP, particularly when it is applied in the form of U-wraps with adequate anchorage and several layers. It is important to comprehend the influence of the shear span-to-depth ratio (a/d) in these settings. Such a/d ratios make a beam more susceptible to diagonal tension cracks, resulting in sudden shear failure, Lu and . Leung 2012 [11], especially in the disturbed regions where arch action is limited, Ahmad et al 2013 [12]. When the internal shear capacity is decreased, the external shear strength, utilizing CFRP, becomes necessary. Carefully designed CFRP wraps and CFRP laminates not only bridge the cracks but can also confine the critical regions, especially where the expected reinforcements are lacking. This renders the a/d ratio as an important factor to consider in the selection and optimization of retrofit strategies in engineering design.

3. Strengthening Methods and Parametric Research

Developing the structural performance and the failure mechanisms of reinforced concrete dapped-end beams (DEBs) is a multivariate function of several important parameters. This includes the geometric proportions, reinforcement configurations, material characteristics, and the applied load (nature). These factors combine to dictate the time at which cracking starts, how much it will spread, and the beam's ductility and capacity to sustain shear and moment. This section critically reviews the most influential parameters, focusing on the behavior of DEBs. Furthermore, recent developments in strengthening methods, specifically fiber-reinforced polymer (FRP) applications, and novel reinforcement systems are reviewed based on experimental and analytical studies.

3.1 Shear Span-to-Depth Ratio (a/d)

The shear span-to-depth ratio (a/d) is widely considered a key factor affecting the structural behavior of dapped-end beams (DEBs). When a/d is low (≤1.0), arching action becomes dominant within the disturbance region (D-region), allowing internal forces to be transmitted through compression struts and thus enhancing shear strength. Conversely, higher a/d values reduce this bowing behavior, resulting in a transition toward a flexure-shear interaction and an increase in ductility but a decrease in shear strength. This trend is well-supported in the literature. Lu et al. (2015) [20], Ahmad et al. (2013) [12], and Shakir et al. (2018) [10] observed improved shear performance and increased load capacity in beams with smaller a/d ratios. Kim and Lee (2017) [21] reported a noticeable shift from flexural to diagonal shear failure as the ratio decreased. Tuchscherer and Adebar (2012) [22] confirmed that lower a/d values promote more stable strut formations and reduce diagonal cracking. Additionally, Zhang et al. (2020)[23] highlighted that decreasing a/d leads to smaller shear crack angles, indicating a more direct and efficient internal load path.

These findings confirm that optimizing the a/d ratio, ideally maintaining it at or below 1.0, can significantly enhance shear resistance, improve crack control, and increase the predictability of failure modes in reinforced concrete dapped-end beams.

3.2 Strength of Concrete

The compressive strength of concrete (f′c) plays a significant role in determining the shear capacity of reinforced concrete dapped-end beams (DEBs), particularly within disturbed regions (D-regions) where stress concentrations are high and load transfer relies heavily on strut action. Multiple studies have confirmed that increasing f′c generally leads to enhanced load-carrying capacity. For example, Lu et al. (2003, 2015) [19,1] observed that increasing concrete strength from 34 MPa to 69 MPa resulted in significant gains in shear strength. Similarly,Aswin et al. (2015) [2] reported a 51.9% improvement in ultimate load capacity when high-strength concrete (79 MPa) was selectively used in the nib region, demonstrating the effectiveness of localized material enhancement.

However, the relationship between compressive strength and shear performance is nonlinear. Beyond certain thresholds typically above 70–80 MPa, the benefits of increased strength begin to plateau. High-strength concrete (HSC), despite its superior compressive resistance, tends to exhibit lower ductility and limited strain capacity, making it more susceptible to brittle failure in regions with complex stress states. Furthermore, its reduced deformability can interfere with the formation of efficient strut-and-tie mechanisms, especially under combined shear and torsional loading. As such, while HSC can enhance shear performance and delay cracking, its application in DEBs should be accompanied by sufficient transverse reinforcement, steel or synthetic fibers, or confinement strategies to mitigate brittleness and ensure a more ductile structural response.

3.3 Reinforcement of Hangers and Nibs

The quantity, spacing, and placement of hanger reinforcement are critical to the structural behavior of dapped-end beams, particularly within the disturbed regions (D-regions) adjacent to the re-entrant corner. Inadequate reinforcement detailing, whether in amount, anchorage, or geometry, often leads to premature cracking, stress concentration in tension zones, and brittle failure mechanisms. Experimental findings by Desnerck et al. (2016) [3] demonstrated that the removal or omission of essential reinforcement components, such as diagonal bars or U-shaped nib bars, resulted in a significant reduction in load-carrying capacity up to 39% in some specimens. These elements are essential for forming a reliable internal strut-and-tie mechanism that facilitates stable and predictable stress transfer in geometrically discontinuous regions. Likewise, Peng (2009) [9]showed that closely spaced hanger bars with sufficient anchorage lengths improved the shear resistance by as much as 44%, while also delaying the onset of diagonal cracking and limiting crack widths. These findings underscore the importance of proper reinforcement detailing in enhancing strength and ductility.

Moreover, nib geometry plays a key role in force distribution. Wang et al. (2005)[4] recommended that the nib depth should be no less than 0.45h (where h is the total beam depth) to ensure effective load transmission through the nib into the support. This geometrical threshold helps maintain the integrity of the compression strut and prevents premature failure at the nib-support interface. External strengthening methods become essential when internal reinforcement is insufficient due to construction errors, deterioration, or poor detailing. Techniques such as carbon fiber reinforced polymer (CFRP) wrapping or bonded steel plates can replicate the structural role of missing internal bars. For instance, U-wrap CFRP configurations can function as external hanger elements, bridging cracks and providing confinement around critical zones like the re-entrant corner. Therefore, a thorough understanding of internal reinforcement behavior is fundamental for developing efficient and targeted strengthening solutions for DEBs in disturbed regions.

3.4 Strengthening Shape and Inclination

The geometry and orientation of reinforcement significantly influence the internal stress flow in dapped-end beams (DEBs), especially within disturbed regions prone to diagonal tension failure. Even modest adjustments in reinforcement layout can alter the distribution of stresses and enhance resistance to cracking and shear. Table 3.1 summarizes key experimental findings on reinforcement configurations that affect the performance of DEBs

Table(3-1) Summary of Experimental Studies on Reinforcement Configurations in Dapped-End Beams

No.	Study	Reinforcement Type	Key Findings
1	Liem (1983)	45° Inclined bars	The load capacity nearly doubled compared to horizontal bars
2	Wang et al. (2005)	Bent (hooked) bars	Improved diagonal crack control and confinement
3	Desnerck et al. 2018	Absence of U-bars	Observed 75° crack angles, indicating poor stress path alignment

Beyond the results in Table 3.1, numerous studies have underscored the importance of inclined and bent reinforcement in improving structural behavior. Rahman et al. (2020)[25] conducted an experimental investigation into the combined use of transversely inclined steel bars and externally bonded CFRP sheets in strengthening reinforced concrete dapped-end beams. Their findings revealed improved crack control, higher load-bearing capacity, and a shift toward more ductile failure modes particularly in specimens with insufficient internal reinforcement. These results were reinforced by the work of Alhassan et al. (2021) [24], who, through both experimental testing and numerical simulations, demonstrated that inclined reinforcement leads to more favorable stress distribution and improved performance of concrete struts.

Further support came from Metzger et al. (2022)[27], whose finite element analyses traced stress trajectories in DEBs and highlighted the effectiveness of aligning reinforcement with principal tensile stress paths. Their study showed that placing reinforcement along these paths, typically at an incline, enhances strut integrity and minimizes stress concentrations, especially around re-entrant corners. This evidence underscores the importance of reinforcing strategies that align with the natural flow of internal forces. When used alongside external CFRP laminates such as U-wraps or side-bonded layers, inclined reinforcement contributes to a hybrid strengthening system that can compensate for construction deficiencies and address site-specific structural challenges.

In contrast, the absence of inclined or diagonally oriented bars often results in ineffective load transfer, vertical crack formation, and brittle failure modes. Desnerck et al. (2018)[13] observed such outcomes in specimens lacking diagonal reinforcement, reporting vertical cracking and localized delamination. In these cases, well-designed external CFRP systems can simulate the function of missing internal bars by enhancing confinement and reestablishing load path continuity.

In conclusion, both internal and external reinforcement orientation should be treated as a fundamental aspect of dapped-end beam design. Inclined reinforcement offers a robust and adaptable solution to improve structural resilience in disturbed regions.

3.5 FIBER REINFORCED CONCRETE (FRC)

dapped-end beams shows significant promise for enhancing structural performance, especially in disturbed areas where traditional reinforcement is limited due to congestion or shape constraints. Among various fiber types, hooked-end steel fibers are particularly effective at reducing crack widths, improving post-cracking ductility, and increasing energy absorption. Mohamed and Elliott (2008)[8] conducted a detailed experiment adding 1% hooked-end steel fibers into self-compacting concrete (SCC) dapped-end beams. Their results revealed a substantial increase in shear capacity and a notable delay in the onset of diagonal cracking. This improvement was attributed to the strong bond between steel fibers and the concrete matrix, enabling fibers to act as bridges that transfer tensile forces across cracks in the compression zone. Unlike traditional stirrups, which are spaced apart and dependent on orientation, steel fibers are evenly distributed throughout the concrete. This constant presence provides effective crack bridging, especially in critical areas like the nib and reentrant corners, known for high stress concentrations and a risk of brittle failure. The benefits of fiber reinforcement are even greater when used in SCC, which ensures uniform fiber dispersion without mechanical vibration, thereby improving constructability and structural integrity. Beyond crack control, steel fibers enhance the material's resistance to tension softening by limiting stress drops after crack initiation. This delayed reduction in tensile strength results in a more ductile failure mode and higher energy dissipation under load. Consequently, FRC offers a practical and efficient way to improve ductility, durability, and failure predictability of dapped-end beams, particularly where traditional reinforcement placement is restricted.

3.6 CFRP Sheet Strengthening

Externally bonded Carbon Fiber Reinforced Polymer (CFRP) sheets represent one of the most effective retrofitting techniques for restoring and enhancing the structural capacity of deficient dapped-end beams (DEBs). These systems offer a high-strength yet lightweight solution, particularly suitable for regions with inadequate internal reinforcement due to design limitations, damage, or construction errors.

Shakir et al. (2018) [10]conducted an experimental program involving DEBs with up to 60% reduction in internal nib reinforcement. Their findings showed that CFRP-retrofitted specimens regained approximately 85% of their original load-carrying capacity, with some configurations even exceeding the initial shear strength. Optimal performance was achieved when CFRP sheets were applied along the predicted crack trajectories, typically inclined between 30° and 45°, ensuring alignment with the principal tensile stress paths and maximizing the fiber bridging effect across diagonal cracks. Despite these advantages, several limitations affect the effectiveness of CFRP strengthening. Premature debonding remains the most critical issue, where CFRP delaminates from the concrete surface before reaching its full tensile capacity. This often results from insufficient surface preparation, inadequate anchorage lengths, or stress concentration at sharp corners, especially around the re-entrant zone. The complexity of stress distribution in disturbed regions (D-regions) worsens these vulnerabilities, making effective confinement and anchorage strategies essential. Researchers recommend U-wrap configurations, mechanical anchors, and hybrid systems that combine CFRP with other reinforcement methods to address these challenges. Proper substrate preparation, fiber orientation, and anchorage detailing are vital for achieving long-term adhesion and efficient stress transfer. When carefully designed and implemented, CFRP systems not only restore shear strength but also improve post-cracking ductility, delay brittle failure, and enhance overall confinement, making them particularly advantageous for retrofitting shear-critical D-regions in DEBs.

3.7. Limitations of Design Codes and Detailing Provisions

Despite the widespread adoption of standardized design methodologies in major building codes, recent research has highlighted several critical shortcomings in their ability to accurately capture the complex behavior of disturbed regions in dapped-end beams (DEBs). Among the most significant limitations are the neglect of anchorage effects, reliance on linear elastic stress assumptions, and oversimplified representations of nonlinear behavior in D-regions. These shortcomings can lead to either overly conservative designs requiring unnecessary reinforcement or unsafe underestimation of structural demands. For example, Aswin et al. (2014) [14] found that while British Standard BS 8110 and Eurocode 2 generally produced conservative predictions, their accuracy varied considerably across different reinforcement configurations. This variability is primarily due to simplified analytical assumptions that do not fully account for the interaction between load paths, confinement effects, and discontinuities near the nib-support interface. Similarly, the PCI Design Handbook (1999)[16] and earlier editions of ACI 318[6] were shown to underestimate ductility demands and overlook crucial anchorage detailing, increasing the risk of brittle failure in regions with high strain gradients and complex stress distributions. Even advanced analytical approaches such as the Strut-and-Tie Model (STM), although more rational and structurally grounded, are not exempt from limitations. Desnerck et al. (2016)[3] and Lu et al. (2015)[1] observed that STM-based designs frequently require additional reinforcement to satisfy the assumed strut geometries and force equilibrium conditions. Without proper calibration against experimental data, STM may produce either excessively conservative outcomes or unsafe assumptions regarding anchorage and crack confinement.

To bridge these gaps, modern design approaches should integrate experimental validation, nonlinear finite element analysis (FEA), and performance-based detailing strategies specifically tailored for D-regions. Such integration enhances the accuracy, efficiency, and safety of new designs and retrofit interventions involving reinforced concrete dapped-end beams.

4. Summary and Design Recommendations

This study has reviewed the structural behavior, design considerations, and strengthening methods associated with non-prestressed reinforced concrete dapped-end beams (RC-DEBs). Through a critical examination of experimental findings, theoretical models, and code provisions, several key conclusions have emerged:

•Geometric discontinuities, particularly at the re-entrant corner, generate localized disturbed regions (D-regions) prone to diagonal cracking and brittle failure.

•The shear span-to-depth ratio (a/d) is dominant in governing failure mechanisms. Lower a/d values (<1.0) enhance arching action and compressive strut formation, improving shear performance.

•While increasing concrete compressive strength raises shear capacity, the improvement is nonlinear and limited by brittle behavior at higher strengths.

•Reinforcement detailing, including the configuration and anchorage of hanger and nib reinforcement, critically influences crack control, confinement, and load-carrying capacity.

•The application of steel fiber-reinforced concrete (SFRC), especially in self-compacting concrete mixes, enhances post-cracking ductility and reduces reinforcement congestion in disturbed zones.

•CFRP strengthening systems, when properly anchored and aligned with principal stress paths, effectively restore or enhance shear resistance, particularly in deficient or retrofitted beams.

•Existing design codes and STM approaches, while providing a foundation, often fail to capture nonlinear stress states, anchorage effects, and confinement demands in D-regions.

These insights highlight the need for improved design detailing, the integration of fiber and composite materials, and the use of nonlinear finite element models to accurately predict DEB behavior. Future research should emphasize hybrid reinforcement systems, parametric calibration of STM, and the validation of analytical models through full-scale testing in torsion and combined loading scenarios.

These insights highlight the need for improved design detailing, the integration of fiber and composite materials, and using nonlinear finite element models to accurately predict DEB behavior. Based on the findings of this review, the following practical design strategies are recommended to enhance the strength, ductility, and reliability of reinforced concrete dapped-end beams (RC-DEBs):

1. Adopt Strut-and-Tie Modeling (STM) in D-regions to capture nonlinear force trajectories and enhance reinforcement detailing accuracy. (ACI 318-19 Appendix A)[6]
2.Limit the shear span-to-depth ratio (a/d) to ≤1.0 to promote arching action and delay diagonal cracking. (Lu et al., 2015)[1]
3.Ensure nib depth ≥ 0.45h for effective force transfer and support interaction. (Wang et al., 2005)[4]
4.Replace vertical stirrups with inclined or bent bars aligned along principal tensile stress trajectories to improve crack resistance. (Kim & Lee, 2017)[21]
5.Provide hanger anchorage≥1.7× development length near the re-entrant corner to prevent anchorage-related failures. (PCI Handbook; Desnerck et al., 2016)[16,3]
6.Use steel fiber-reinforced self-compacting concrete (SFRC-SCC) to enhance post-cracking ductility and reduce reinforcement congestion. (Mohamed & Elliott, 2008)[8]
7. Apply CFRP sheets at 30–45° orientations, utilizing U-wrap configurations

and proper anchorage detailing to restore shear capacity. (Shakir et al., 2018)[10]

8.Incorporate nonlinear finite element analysis (FEA) in design workflows to better account for local stress states and anchorage behavior. (Desnerck et al., 2018)[13]

9. Promote hybrid systems combining SFRC, CFRP, and advanced fiber types (e.g., basalt or glass FRPs) for enhanced resilience. (Alhassan et al., 2022)[24]

These recommendations provide a practical framework for both current design applications and future experimental research to optimize the performance of dapped-end beams, especially under critical shear and torsional demands.

References

[1] W. Y. Lu, T. C. Chen, and I. J. Lin, “Shear strength of reinforced concrete dapped-end beams with shear span-to-depth ratios larger than unity,” J. Mar. Sci. Technol., vol. 23, no. 4, pp. 431–442, 2015. https://doi.org/10.6119/JMST-015-0511-1

[2] M. Aswin, B. Mohammed, M. S. Liew, and Z. I. Syed, “Root cause of reinforced concrete dapped-end beams failure,” Int. J. Appl. Eng. Res., vol. 10, no. 22, pp. 42927–42933, 2015.

[3] P. Desnerck, J. M. Lee, and C. T. Morley, “Impact of the reinforcement layout on the load capacity of reinforced concrete half-joints,” Eng. Struct., vol. 127, pp. 227–239, 2016. https://doi.org/10.1016/j.engstruct.2016.08.061

[4] Q. Wang, Z. Guo, and P. C. J. Hoogenboom, “Experimental investigation on the shear capacity of RC dapped-end beams and design recommendations,” Struct. Eng. Mech, vol. 21, no. 2, pp. 221–235, 2005. https://doi.org/10.12989/sem.2005.21.2.221

[5] K. H. Yang, A. F. Ashour, and J. K. Lee, “Shear strength of reinforced concrete dapped-end beams using mechanism analysis,” Proc. ICE – Struct. Build. vol. 164, no. 3, pp. 161–175, 2011. https://doi.org/10.1680/stbu.9.00006

[6] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary*, American Concrete Institute, Farmington Hills, MI, 2019.

[7] A. H. Mattock and T. C. Chan, “Design and behavior of dapped-end beams,” PCI J. vol. 24, no. 6, pp. 28–45, 1979. https://doi.org/10.15554/pcij.11011979.28.45

[8] R. N. Mohamed and K. S. Elliott, “Shear strength of short recess precast dapped-end beams made of steel fibre self-compacting concrete,” in Proc. 33rd Conf. on Our World in Concrete & Structures, Singapore, 2008.

[9] T. Peng, "Influence of detailing on response of dapped-end beams", M.Sc. thesis, McGill Univ., Montreal, Canada, 2009.

[10] Q. M. Shakir, B. B. Abd, and A. T. Jasim, “Experimental and numerical investigation of self-compacting reinforced concrete dapped-end beams strengthened with CFRP sheets,” J. Univ. Babylon Eng. Sci., vol. 26, no. 7, 2018. https://doi.org/10.29196/jubes.v26i7.1482

[11] Y. Lu and C. K. Y. Leung, “Modeling the shear behavior of dapped-end beams using refined STM,” J. Struct. Eng. (ASCE), vol. 138, no. 8, pp. 982–993, 2012.

[12] S. Ahmad, A. Elahi, J. Hafeez, M. Fawad, and Z. Ahsan, “Evaluation of the shear strength of dapped-ended beams,” Life Sci. J., vol. 10, no. 3, 2013.

[13] P. Desnerck, J. M. Lee, and C. T. Morley, “Strut-and-tie models for deteriorated reinforced concrete half joints,” Eng. Struct., vol. 161, no. 1, pp. 41–54, 2018. https://doi.org/10.1016/j.engstruct.2018.01.013

[14] M. Aswin, Z. I. Syed, T. Wee, and M. S. Liew, “Prediction of failure loads of RC dapped-end beams,” Appl.Mech. Mater., vol.567, pp.463-468, 2014. https://doi.org/10.4028/www.scientific.net/AMM.567.463

[15] European Committee for Standardization (CEN), EN 1992-1-1: Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings, Brussels, Belgium, 2004.

[16] PCI, *PCI Design Handbook: Precast and Prestressed Concrete, 6th ed., Precast/Prestressed Concrete Institute, Chicago, IL, 1999.

[17] F. J. Vecchio and M. P. Collins, “The Modified Compression Field Theory for reinforced concrete elements subjected to shear,” ACI J., vol. 83, no. 2, pp. 219–231, 1986.

[18] S. K. Liem, "Maximum shear strength of dapped-end or corbel", M.Sc. thesis, Concordia Univ., Montreal, Quebec, Canada, 1983.

[19] W. Y. Lu, I. J. Lin, S. J. Hwang, and Y. H. Lin, “Shear strength of high-strength concrete dapped-end beams,” J. Chin. Inst. Eng., vol. 26, no. 5, pp. 671–680, 2003. https://doi.org/10.1080/02533839.2003.9670820

[20] Y. Lu, J. Xu, and C. Wu, “Effect of a/d ratio on shear behavior of RC beams with web openings,” Eng. Struct, vol. 101, pp. 140–152, 2015.

[21] S. Kim and S.-J. Lee, “Influence of a/d ratio on structural performance of deep beams with web reinforcement,” KSCE J. Civ. Eng., vol. 21, no. 7, pp. 2756–2763, 2017.

[22] A. Tuchscherer and P. Adebar, “Finite element modeling of disturbed regions in reinforced concrete,” ACI Struct. J., vol. 109, no. 3, pp. 365–374, 2012.

[23] H. Zhang, Z. Li, and J. Chen, “Crack propagation in RC beams with varying shear span-to-depth ratios,” J. Struct. Eng., vol. 146, no. 4, 04020030, 2020.

[24] A. M. Alhassan, M. M. Mahmod, and S. A. Al-Shaarbaf, “Numerical investigation of stress trajectories in dapped-end beams with inclined reinforcement,” Eng. Struct., vol. 256, 114001, 2022.

[25] M. M. Rahman, M. Z. Jumaat, and A. B. M. S. Islam, “Hybrid strengthening of RC beams using inclined steel bars and CFRP sheets,” Constr. Build. Mater vol. 246, 118479, 2020.

[26] M. F. Ruiz and A. Muttoni, “On development of suitable stress fields for structural concrete,” Struct. Eng. Int., vol. 17, no. 3, pp. 187–195, 2007.Concrete”

[27] Metzger, J., Brosens, K., & Vandewalle, L.“Stress field-based design of disturbed regions in reinforced concrete: A computational approach,”Structural Concrete, vol. 23, no. 4, pp. 2156–2171. . (2022) https://doi.org/10.1002/suco.202100413