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An Overview of Openings in Concrete Deep Beams-A Comprehensive Analysis

Bilal Alhammud[1], Dr. Ayşe Yeter Günal[2], and Rajab Alkhatib[3]

[1,2,3] Department of Civil Engineering, Faculty of Engineering, Gaziantep University, Türkey

Correspondence should be addressed to Bilal Alhammud; sarisara121@gmail.com

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ABSTRACT- The study of deep beams with openings in their webs and how to reinforce them is crucial for ensuring strong and effective structures. This collection of research examines various aspects of the topic, including the use of externally bonded composites and fiber-reinforced polymers (FRP). The studies carefully investigate the failure mechanisms of these beams, their response to loads and deflections, improvements in their shear capacity, and the effects of the size and placement of the openings. Collectively, these studies provide valuable insights into the reinforcement of deep beams, contributing to the overall knowledge in structural engineering.

KEYWORDS- CFRP Strips, Deep Beams, Finite Element, Mode of Failure, Opening Size, Openings, Parametric Study, Shear, Strengthening, Reinforced Concrete

I. INTRODUCTION

Reinforced concrete (RC) deep beams are structural members characterized by their large height relative to their span lengths, thus gaining the definition of "deep". This feature is generally defined by an aperture-to-depth ratio of four or less; loads are typically concentrated within twice the depth of the member. Their behavior is quite complex, especially in terms of shear capacity, due to the interaction between nonlinear deformation and non-bending behavior after crushing. These deep beams find application in various engineering contexts, especially in marine structures where their durability is important. They can also integrate web exploits for easier access, but such changes can create difficulties. Mechanical modifications made to meet specific functional requirements may inadvertently compromise the beam's shear capacity and overall safety. Similarly, introducing openings for plumbing and ducts can further complicate the behavior of joists, leading to structural weaknesses and safety concerns. Overcoming these challenges often involves implementing pre-planned or post-opening strengthening measures to improve the structural integrity of deep beams. Fiber reinforced polymer (FRP) composites, such as carbon fiber reinforced polymer (CFRP), are frequently used in these reinforcement works due to their high strength/weight ratio and corrosion resistance properties [4][5][12].

However, despite the increasing importance of deep beams and the use of FRP strengthening techniques, research in this area is still relatively limited. The paucity of comprehensive studies highlights the urgent need for further research and investigation into the behavior of deep beams, especially when exposed to different loading conditions and strengthening strategies involving FRP composites. These research efforts are crucial to advancing our understanding of deep beam mechanics and increasing the effectiveness of FRP strengthening methods in providing structural flexibility and integrity.

II. LITRATURE REVIEW

Enhancement of Reinforced Concrete Deep Beams via the Incorporation of Web Apertures and Fiber-Reinforced Polymer (FRP) Laminates: Adding web openings to reinforced concrete deep beams significantly reduces the shear strength [9]. In particular, larger apertures, especially those with a/D = 0.47, show the most significant reductions. Circular grooves can reduce shear strength by up to 61.94% compared to solid deep beams, while square grooves can reduce shear strength by up to 72.54% compared to their massive counterparts. Regarding the effectiveness of reinforcement techniques in increasing shear strength, the study proved that reinforcement using U-shaped laminated EB-GFRP fabrics along the entire length of the beam is beneficial in increasing shear strength. Combining EB-GFRP fabrics with GAF in shear openings results in increased shear strength. Using both EB-GFRP and GAF fabrics can increase shear strength by up to 64% compared to unreinforced beams. Experimental results were compared with theoretical predictions from previous studies to assess accuracy. This comparison aims to evaluate the reliability of theoretical models in predicting the shear behavior of web-span deep beams. The study confirms the effectiveness of using EB-GFRP fabrics and GAF techniques to strengthen RC deep beams containing circular and square web openings, mitigating the inherent reduction in shear strength associated with these openings.

Deep beams are a very important aspect to understand their structural behavior and flexibility [7]. The study included sixteen different R.C. uses a state-of-the-art approach using finite element analysis via ABAQUS software to formulate the model. Deep beams. These models include different aperture sizes and are subject to two different shear/depth ratios, allowing a comprehensive investigation of the structural response under different conditions. The validation phase is an integral part of the research where the models are subjected to rigorous scrutiny using the concrete damage plasticity (CDP) model. This validation process ensures the accuracy of the simulated results by comparing them with experimental data obtained from previous experimental studies. Encouragingly, the results show remarkable agreement between model predictions and real-world experimental observations, improving the reliability of computational simulations. One of the most important results is the verification that finite element models effectively capture the precise behavior exhibited by RC. Deep beams. Moreover, the inclusion of CFRP sheets provides many great benefits. In particular, these include a significant improvement in damage load capacity and a significant reduction in flexural crack initiation and propagation. Perhaps most interestingly, the study demonstrates the important role CFRP plays in delaying the onset of initial radial cracking. This effect is especially evident in models with a cutting aperture/depth ratio of 0.9; here CFRP sheets clearly increase the load threshold required to form the first diagonal crack. However, although this effect is still noticeable in models with a cut-to-depth ratio of 1.1, the magnitude of the change is relatively slight. In summary, the research confirms the effectiveness of CFRP sheets as a viable strategy to enhance the performance and flexibility of R.C. Deep beams. Through a careful combination of computational modeling and experimental validation, this study provides valuable insight into the complex interplay between material composition, structural geometry, and load-carrying capacity in reinforced concrete structures.

III. FINITE ELEMENT INVESTIGATION OF REINFORCED CONCRETE DEEP BEAM FEATURING A SUBSTANTIAL APERTURE

The study performed a comprehensive evaluation through nonlinear finite element analyzes on deep live beams with large spans [3] and evaluated their structural behavior under three different design methodologies: Kong. F.K., Mansour and STM method (ACI 318-14). The results showed that all three methods provided satisfactory ultimate load capacities, demonstrating their suitability for such structural configurations. However, a closer examination of the service load revealed a definitive scenario. While the width of the cracks near the middle part of the upper beam exceeded Kong's design limit. F.K. pointed out a potential security vulnerability and stated that both the Mansour method and the STM method maintained crack widths within acceptable parameters. This discrepancy highlights the need for careful examination of crack control mechanisms, especially in designs using Kong. F.K methodology indicating a potential need for additional reinforcement to reduce crack propagation. Further analysis confirmed the effectiveness of Mansour's approach in the design of deep beams with large spans. By visualizing concrete members surrounding spans to follow Vierendeel truss movement and eccentrically bearing truss members at the top and bottom of the span, the Mansour method demonstrated superior performance in terms of failure loads as well as cost-effective reinforcement rates. Although the total amount of steel used between Kong is similar. F.K. and as Mansour approached, visible differences in the arrangement of the steel within the structural members became apparent. Additionally, although the STM method provided better ductility and structural strength, it required approximately 25% more reinforcement than the other two methods. Regarding deflection, the three design models successfully met the prescribed limits, confirming their structural integrity under constant loading conditions. However, the study's focus on static loads requires further investigation of the effects of cyclic loading; this can provide deeper insights into the long-term performance and durability of the designed deep beams. Fundamentally, although the three design methodologies appear promising in overcoming the challenges posed by wide-aperture deep beam transmission, each approach offers distinct advantages and considerations that deserve careful consideration in practical engineering applications.

IV. THE USE OF ANSYS PROGRAM FOR ANALYZING THE BEHAVIOR OF DEEP BEAMS WITH OPENINGS

Using ANSYS 11 software, a cohort of eighteen specimens underwent meticulous analysis to scrutinize the impact of variables such as web orifice characteristics, concrete compressive strength (f'c), and stirrup reinforcement on the shear-to-effective-depth ratio (a/d) [1]. Employing the Solid65 finite element model for Self-Consolidating Concrete (SCC) beams and the Link 180 model for steel reinforcement, each specimen, measuring 1200 mm in length, 440 mm in width, and 110 mm in depth, was subjected to the boundary conditions of simple support and subjected to dual concentrated point loads. Remarkably, diminishing the shear-to-effective-depth ratio (a/d) from 1.2 to 0.8 engendered a notable 20% augmentation in the ultimate capacity. Furthermore, a reduction of 30.5% in the dimensions of square apertures yielded a discernible 9% escalation in ultimate capacity. Notably, circular perforations outperformed their geometric counterparts. Additionally, the compressive strength of concrete exerted a profound influence on the structural capacity of SCC beams. Elevations in reinforcement ratios correlated positively with augmented ultimate load-bearing capacity. Moreover, diminished inter-node spans correlated with heightened ultimate capacity.

Overall, the study highlights the importance of a/d ratio, concrete strength and reinforcement in determining SCC deep beam capacity and provides recommendations in favor of circular web spans for optimum performance.

The steel fiber enhanced stiffness, ultimate load, and failure deformation, though the effect diminished with higher stirrup ratios [13]. After diagonal cracks formed, steel fiber reduced strains and crack widths, increased the number of cracks, and lowered crack height. The shear capacities calculated using ACI544.4R matched the experimental values, whereas the CECS38:2004 formula required adjustments to accurately predict shear capacities.

Figure 1 shows that adding steel fiber to the beams resulted in more vertical and diagonal cracks with reduced spacing, as the fibers transferred stress to the surrounding concrete. This process generated additional or branching cracks and significantly lowered the height of vertical cracks between loading points.

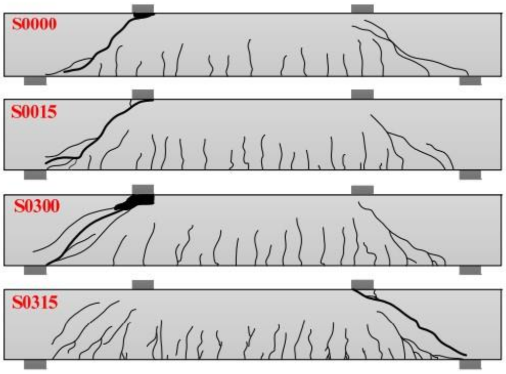

Figure 1: Failure Style [13]

There was a study conducted an evaluation of 61 RHSSCC deep beams with various web openings [6]. The study focused on the size (75 mm, 50 mm), shape (square, circular, rhombus), and position (upper/lower neutral axis, in/out load path) of the openings. The key findings are as follows:

- Self-compacting concrete (SCC) is optimal for narrow, congested deep beams.
- Openings reduced ultimate and cracking loads by 5-55%.
- All beams with openings failed in shear.
- Larger openings decreased load capacity and ductility.
- Rhombus-shaped openings outperformed square and circular shapes.
- Openings in the load path reduced capacity and ductility more significantly.
- Openings below the neutral axis lessened load capacity reduction, except for centered openings.
- Symmetrical openings caused the most significant load reduction.

All tested deep beams failed in shear, with diagonal cracks forming around openings as shown in figure 2. Square openings caused high-stress concentrations, while circular and rhombus openings distributed stress more evenly. Larger openings increased diagonal cracks. Openings below the neutral axis caused more support-side cracks. Symmetrical openings had cracks on both sides, while unsymmetrical openings had more on one side. For upper openings, flexural cracks stopped before the compression strut, followed by shear cracks. Centered openings had vertical flexural cracks propagating to the opening level.

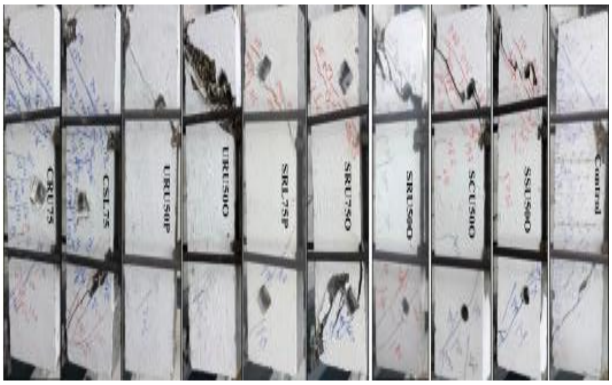

Figure 2: Examples for Deep Beam Specimens [6]

CFRP strips were used to strengthen RCCDBs with large openings [8]. The strips increased specimen capacity by 17% and reduced ultimate deflection by 10% as table 1 shows. Larger openings saw improved ultimate capacity and deflection when strengthened. The study also found that ultimate capacity decreased by 21% and initial stiffness by 35% due to the presence of openings.

Table 1: Experimental Results [8]

Specimen	Initial Crack Load (kN)	Ultimate Capacity (kN)	Ultimate Deflection (mm)	Initial Stiffness (kN/mm)	Mode of Failure
CDB-Solid	200	730	2.4	1745	Shear failure
CDB-O-U	140	580	1.7	1142	Bearing failure
CDB-O-S	210	680	2.4	1390	Bearing failure

Specimen CDB-Solid displayed flexural and shear cracks, resulting in shear failure as shown in figure 3. Additionally, Specimen CDB-O-U had initial cracks at the opening corners, leading to a 30% reduction in the initial crack load and resulting in bearing failure. The CFRP strips redirected loads, increasing the initial crack load by 50% and preventing shear cracks, although debonding occurred at higher loads.

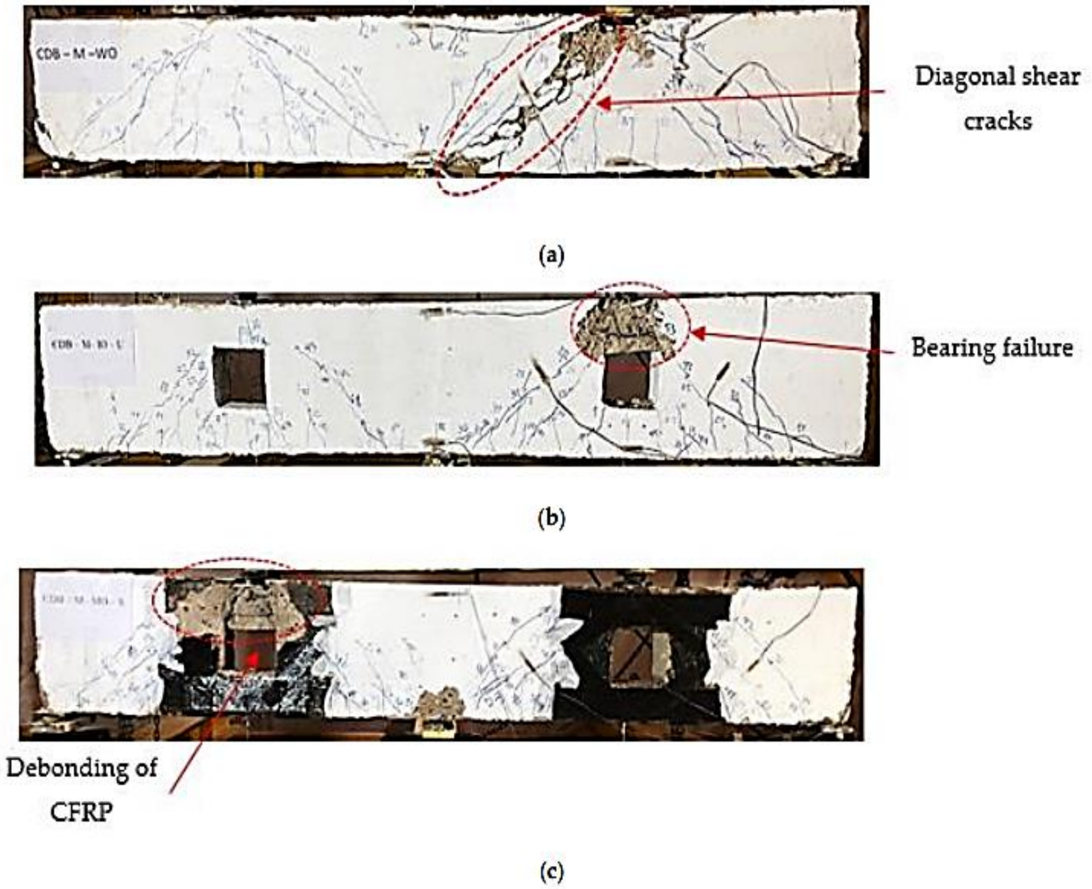

Figure 3: Failure Modes of Tested Specimens: (a) Specimen CDB–Solid, (b) Specimen CDB–O–U, (c) Specimen CDB–O–S [8]

Figure 4 and table 2 compare the experimental and FE results for the deformations of the tested specimens. The specimen responses were very close during the elastic stage, but the FE results became slightly stiffer at yielding load due to assumed full contact between concrete and strengthening strips. Despite this difference, there was good overall agreement, allowing for the use of the validated FE model in a parametric study.

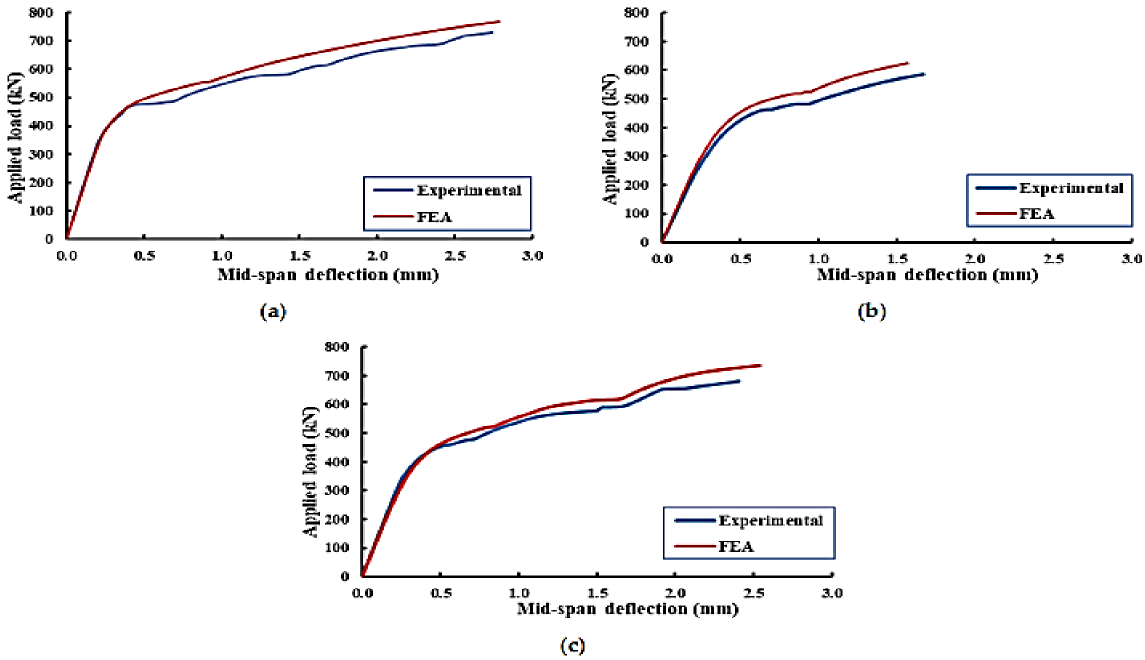

Figure 4: Load mid-span deflection curves for the experimental and FE results. (a) Specimen CDB–Solid; (b) specimen CDB–O–U; (c) specimen CDB–O–S [8]

Table 2: Comparisons between the Experimental and FE Results [8]

Specimen	Ultimate Capacity (kN)		% Change *	Ultimate Deflection (mm)		% Change *
	Exp.	FE		Exp.	FE	
CDB–Solid	730	770	+ 5.5	2.5	2.8	+ 12
CDB–O–U	580	625	+ 7.7	1.7	1.6	– 5.9
CDB–O–S	680	735	+ 8.1	2.4	2.5	+ 4.2

The cyclic behavior of RC beams with openings strengthened using CFRP sheets have been studied [11]. Seven beams were tested, including one control and six with openings. CFRP significantly improved maximum strength by approximately 66.67% and ultimate displacement by 77.14%. Finite element analysis confirmed the experimental results.

The study delved into the intricate interplay of factors such as the dimensions and placements of these openings, along with the configuration of web reinforcements [2]. Notably, the research identified two distinct failure modes, delineated by the positioning of the web apertures: one occurring within the interior shear spans and the other within the exterior ones. Beams with openings situated in the interior shear spans succumbed to failure owing to the formation of diagonal cracks emanating from the junctures of the web apertures and the boundaries defined by load and central support plates. Conversely, those with openings positioned in the exterior shear spans exhibited more severe failure, characterized by the propagation of significant diagonal cracks traversing both interior and exterior shear spans. Significantly, the investigation highlighted a pronounced reduction in beam capacity associated with openings situated within interior shear spans compared to their counterparts within exterior shear spans. Furthermore, it underscored the pivotal role played by vertical web reinforcement in influencing beam capacity, surpassing the impact of horizontal reinforcement. Moreover, the study presented an upper-bound analysis elucidating the observed failure mechanisms and devised design equations predicated on the empirical insights gleaned from the experiments.

Shear failure, a type of structural concrete failure, often occurs suddenly, making it necessary to prevent it, especially since flexural failure is more likely than shear failure in beams [10]. An experimental study examined the structural response of deep reinforced concrete (RC) beams with reinforced web spans using carbon fiber reinforced polymer (CFRP) composites added externally to the shear zone. The study investigated various aspects of structural behavior, including damage mode, crack formation, load-deflection characteristics, stress distribution, and the effect of reinforcement. Nine deep-slit concrete beams reinforced with CFRP and a control beam without slots were fabricated and subjected to four-point static bending until failure. The results showed that increasing the slit size led to a decrease in shear strength of up to 30%, resulting in a decrease in bearing capacity. However, adding more layers of carbon fiber-reinforced polymer can increase durability. The use of CFRP coating significantly increased the shear strength of deep reinforced concrete beams, increasing them by 10% to 40%. The most effective number of CFRP layers for deep beams with span sizes of 150 mm and 200 mm was determined to be two and three layers, respectively.

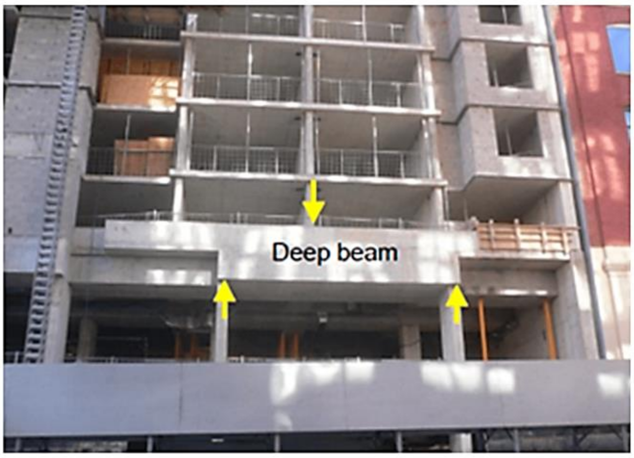

Figure 5: Deep Beam [10]

According to figure 5, we notice the construction site the highlighted deep beam plays a vital role in supporting the floors above. Its increased depth ensures stability and efficient load distribution.

V. DISCUSSION

While the mentioned research provides a comprehensive overview of various research studies focusing on deep-openings RC beams, there are also several areas that can be criticized for their lack of depth and analysis. First, the researches do not comprehensively discuss the potential limitations and biases of the cited studies. Every research effort has limitations regarding sample size, experimental conditions, or theoretical assumptions. Failure to address these limitations undermines the reliability and applicability of the findings presented. It should also benefit from a more critical examination of the methodologies used in the studies. It is necessary to examine the experimental procedures, numerical simulations and analytical techniques used to ensure its validity and reliability. Without critically evaluating these methodologies, readers may wonder how robust the research findings are. Additionally, there is a lack of discussion regarding conflicting or conflicting findings across studies. Investigations across various domains frequently yield divergent outcomes, necessitating the acknowledgment and reconciliation of such disparities to foster a more nuanced comprehension of the subject matter. Ignoring conflicting evidence, the text presents a simplistic narrative that may not accurately reflect the complexity of RC long-beam behavior. Additionally, the text may delve more deeply into the implications of research findings for practical engineering applications. Although the studies briefly indicate their importance to structural engineering, a more in-depth analysis of how the results are translated into design guidelines, industry standards, or construction practices would increase their practical utility. Overall, while the text provides a broad overview of research on deep-groove RC beams, it lacks critical analysis, depth, and consideration of conflicting evidence. By eliminating these deficiencies, the text can enable a more detailed and insightful investigation of the subject.

VI. CONCLUSION

This paper provides valuable insights into the behavioral dynamics and fortification of reinforced concrete (RC) deep beams with openings, shedding light on various factors influencing their structural integrity and performance. The collective findings underline the importance of considering factors such as web opening size, reinforcement techniques, concrete strength, and design methodologies in the analysis and strengthening of RC deep beams. By addressing these factors comprehensively, engineers can enhance the structural performance and resilience of deep beam structures, thereby ensuring their safety and longevity in practical engineering applications.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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