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Near-Surface Mounted and Hybrid FRP Strengthening of RC Columns: A Critical Review of Experimental, Finite Element and Analytical Studies

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ABSTRACT

Near-surface mounted (NSM) fibre-reinforced polymer (FRP) reinforcement, used alone or combined with an FRP jacket (hybrid technique), has been proposed for reinforced concrete (RC) columns governed by combined axial force and bending, where code-endorsed jacketing loses efficiency and the compressive contribution of longitudinal fibres is neglected. This paper critically reviews 100 documents on this subject, including the previous experimental, finite element (FE) and soft-computing studies of the authors. The literature is examined from two perspectives. From the experimental perspective, 58 column studies comprising more than 770 specimens are classified into jacket confinement, longitudinal externally bonded and grooving methods, NSM/hybrid columns under cyclic lateral load, NSM/hybrid columns under axial, eccentric and flexural load, and repair of damaged columns; their variables and conclusions are tabulated. A 112-test database and capacity ratios compiled from eleven series show that the mean capacity gain of NSM rises from about 6% under concentric load to about 40% in pure bending, jacketing shows the opposite trend, and the hybrid technique gives the largest gains (30–63%) along the whole interaction diagram. From the numerical perspective, FE, confined-concrete, strain-compatibility and data-driven models are compared. Code-based section analysis that ignores NSM compression underestimated capacity substantially (mean absolute percentage error of 26% concentric and 68% eccentric in one test series), whereas calibrated FE models, moment–curvature models with a bond-limited NSM strain, and fuzzy or ensemble-learning models kept the error at or below 13%. Critical gaps are identified: few monotonic tests on groove geometry, bar type and slenderness; inconsistent load application in eccentric tests; no bond–slip law for NSM bars in compression; scarce cyclic data for hybrid systems; and incomplete reporting that limits data-driven modelling. Recommendations for testing protocols, modelling practice and code development are proposed.

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Introduction

Existing reinforced concrete (RC) structures frequently require strengthening because of deterioration, design or construction errors, changes of occupancy and the revision of design codes. Among the available materials, fibre-reinforced polymer (FRP) composites have been widely adopted owing to their high strength-to-weight ratio, corrosion resistance, non-magnetic nature and speed of installation (Teng, Chen, Smith & Lam, 2002; Bank, 2006; De Lorenzis & Teng, 2007). Columns deserve particular attention because their failure can trigger the collapse of the whole structure.

The strengthening approach endorsed by ACI Committee 440 (2017) for columns is confinement by FRP jackets with fibres oriented transversely, the confined strength being obtained from the design-oriented model of Lam and Teng (2003a). The guide ignores any contribution of longitudinal fibres in compression and allows strength enhancement only when the factored axial force and moment lie above the line joining the origin and the balance point of the unconfined interaction diagram. Jacketing is therefore of limited use when flexure governs, as in capacity-design checks (strong column–weak beam) or when corroded longitudinal bars must be supplemented up to the end sections where the moment is maximum. Conventional alternatives, such as RC or shotcreted steel-cage jackets, enlarge the section, increase stiffness and seismic demand, and are slow to execute (Bournas & Triantafillou, 2009).

Near-surface mounted (NSM) FRP reinforcement, introduced for beams and slabs by ACI Committee 440 (2002), consists of FRP bars or strips bonded with epoxy or mortar inside grooves cut into the concrete cover. Compared with externally bonded reinforcement (EBR), NSM requires surface preparation only inside the groove, mobilises higher bond stresses, delays premature debonding and protects the FRP from impact and environmental attack (De Lorenzis & Teng, 2007). Its bond behaviour (De Lorenzis, Rizzo & La Tegola, 2002; Sharaky, Torres, Baena & Miàs, 2013a; Sharaky, Torres, Baena & Vilanova, 2013b; Seo, Feo & Hui, 2013; Kalupahana, Ibell & Darby, 2013) and its use for flexural and shear strengthening of beams (Badawi & Soudki, 2009; Rizzo & De Lorenzis, 2009; Dias & Barros, 2010; Hajihashemi, Mostofinejad & Azhari, 2011; Jalali, Sharbatdar, Chen & Jandaghi Alaee, 2012; Sharaky, Torres, Comas & Barris, 2014; Dias & Barros, 2013; Dias, Barros & Janwaen, 2018; Abdallah, Al Mahmoud, Khelil, Mercier & Almassri, 2020) are well documented. Over the last two decades, NSM bars placed on the tension and compression faces of columns, alone or confined by an FRP jacket (hybrid technique), have been investigated as a way of increasing flexural and combined axial–flexural capacity.

Previous reviews have addressed confinement models (De Lorenzis & Tepfers, 2003; Ozbakkaloglu, Lim & Vincent, 2013) or NSM strengthening of beams (De Lorenzis & Teng, 2007), but the column application of NSM and hybrid systems has not been reviewed systematically from both the experimental and the modelling standpoints. This paper reviews the literature on NSM- and hybrid-strengthened RC columns, including the authors' previous research (Afzali, Alinejad, Nasrollahzadeh & Kang, 2021; Nasrollahzadeh & Afzali, 2019; Shayanfar, Ghanooni-Bagha & Afzali, 2024a; Shayanfar, Ghanooni-Bagha & Afzali, 2024b; Shayanfar, Ghanooni-Bagha & Afzali, 2024c; Afzali, Eftekhar Afzali, Shayanfar, Ghanooni-Bagha & Afzali, 2025). The objectives are to (i) classify and tabulate the studies, (ii) quantify their scope and outcomes statistically, (iii) appraise them critically, and (iv) identify research needs.

2. Strengthening techniques and code provisions

In the EBR jacket technique, FRP sheets are wrapped with fibres perpendicular to the column axis, providing passive confinement that is activated by lateral dilation. In the NSM technique, a groove is cut (or pre-formed) in the cover, half-filled with adhesive, the bar or strip is pressed in and the groove is filled and levelled. In the hybrid technique, the NSM-strengthened column is subsequently wrapped (Fig. 1(a)). Static evaluation of these techniques requires at least three points of the P–M diagram: pure compression (A), eccentric compression near the balance point (B) and pure bending (C), which are obtained with concentric, eccentric and three- or four-point bending tests, respectively (Fig. 1(b–d)) (Shayanfar et al., 2024a; Shayanfar et al., 2024c).

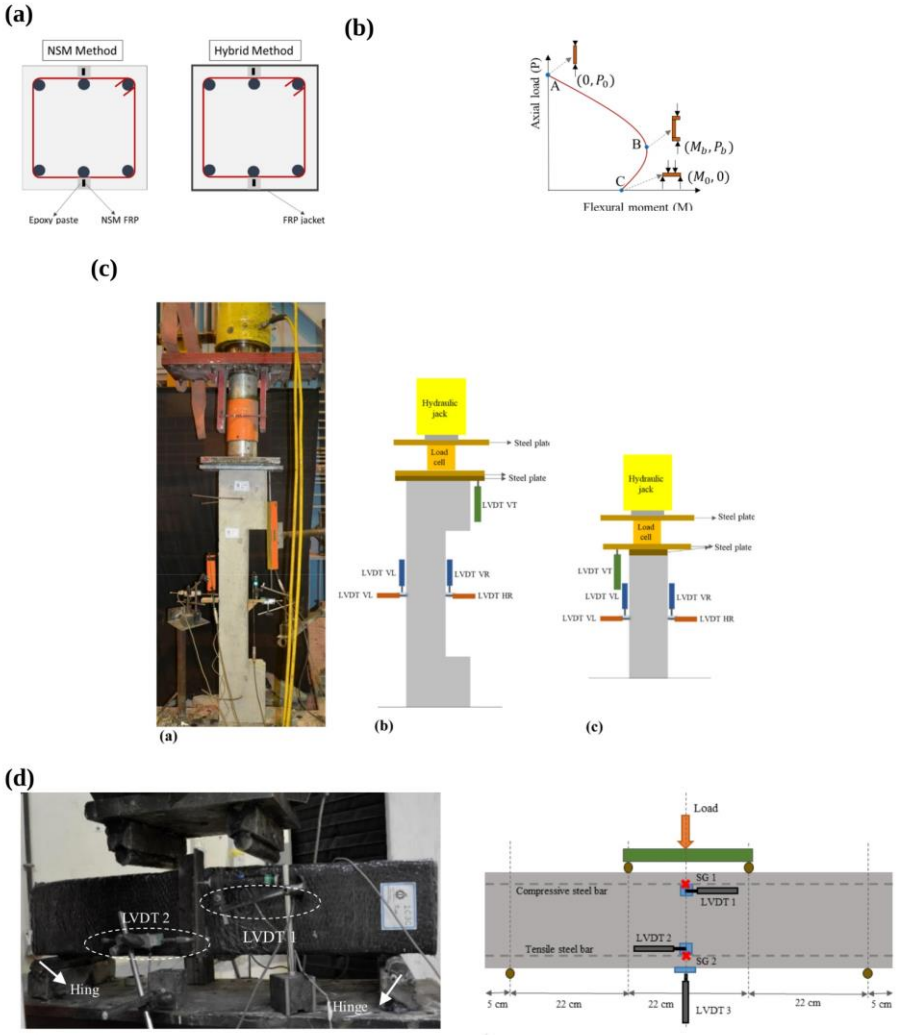

Fig. 1. Strengthening configurations and test arrangements in the authors' previous studies: (a) NSM and hybrid sections; (b) the three key points of the P–M interaction diagram; (c) eccentric and concentric compression tests; (d) four-point bending test. Adapted from Shayanfar et al. (2024a, 2024b, 2024c).

ACI Committee 440 (2017) limits the effective jacket strain to 0.004 under combined loading, applies a strain-efficiency factor (on average 0.55 for CFRP), uses an equivalent circular section for rectangular members with aspect ratio up to 2.0 and side length up to 900 mm, and excludes high-strength concrete (70 MPa or more) unless supported by tests. For NSM, the groove must be

at least 1.5 times the bar diameter (3.0 and 1.5 times the strip thickness and width), the clear spacing between grooves at least twice the groove depth, and the edge distance at least four times the groove depth; the development length is derived from an average bond stress of 6.9 MPa. These NSM rules were calibrated on beams in which the FRP is in tension; whether they are adequate for bars that alternate between tension and compression in columns is an open question.

3. Review methodology and overview of the literature

The review procedure is summarised in Fig. 2. An initial pool of 95 references on FRP-strengthened columns, NSM bond and related modelling was screened to remove duplicates and items without technical content, bibliographic data were completed, and the authors' previous studies and the remaining sources of their test database were added, giving a corpus of 100 documents. Fifty-eight experimental column studies are tabulated; three further sources contribute only to the database statistics of Section 4.4. Experimental column studies were grouped into five sub-categories: FRP-jacket confinement (J), longitudinal EBR and grooving methods (L), NSM and hybrid columns under constant axial load and cyclic lateral displacement (S), NSM and hybrid columns under concentric, eccentric or flexural loading (M), and repair of damaged columns (R). Modelling studies were grouped into FE models, confined-concrete models, section (strain-compatibility or P–M) models and soft-computing models. For each study, the specimens, loading path, variables, failure modes and main conclusions were extracted (Tables 1 and 2). Where test-by-test values were available, capacity ratios and prediction errors were recomputed so that results from different sources could be compared on a common basis.

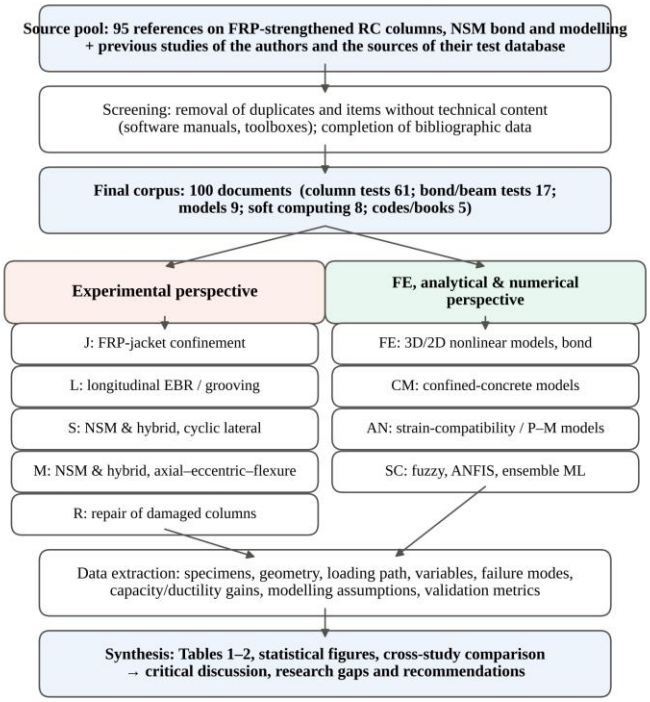

Fig. 2. Framework of the review: source pool, screening, classification into experimental and modelling perspectives, data extraction and synthesis.

Fig. 3(a) shows that research activity accelerated after 2009, with about three quarters of the documents published from 2010 onwards and NSM bond and beam studies concentrated in 2010–2014. Confinement studies (sub-category J) are the most numerous (20 studies, 291 specimens), whereas NSM and hybrid columns under cyclic lateral load are represented by only eight studies and about 60 specimens (Fig. 3(b, c)). The experimental database is dominated by small square specimens tested under concentric compression (Fig. 4): of the 48 studies reporting the number of specimens, the median is 11, and only four studies trace several points of the axial force–moment (P–M) interaction diagram, while a single study tests NSM/hybrid columns in pure bending.

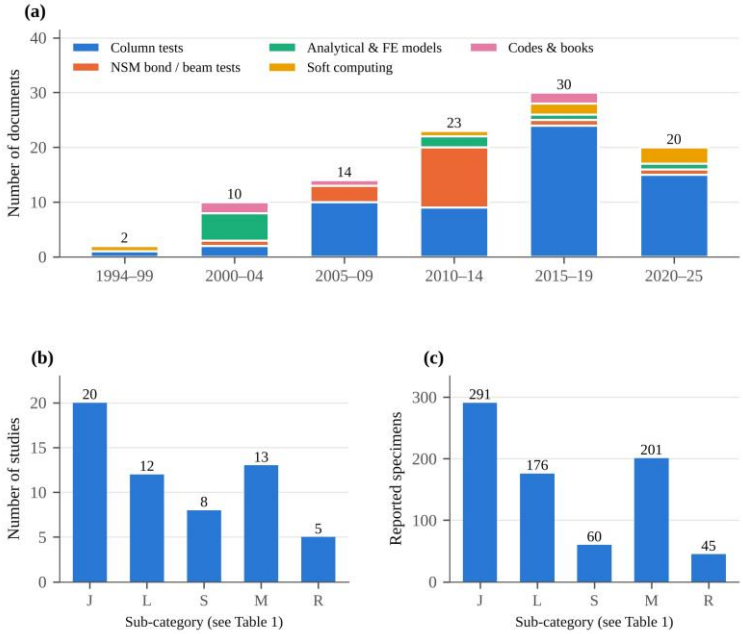

Fig. 3. Statistical overview of the corpus: (a) publication period by category; (b) number of experimental column studies and (c) number of reported specimens in each sub-category (J: jacket confinement; L: longitudinal EBR/grooving; S: NSM/hybrid under cyclic lateral load; M: NSM/hybrid under axial, eccentric or flexural load; R: repair)

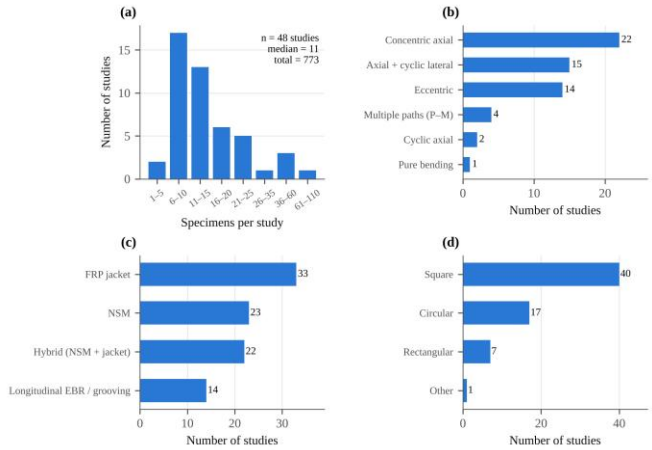

Fig. 4. Characteristics of the experimental column studies: (a) histogram of specimens per study; (b) loading protocol; (c) strengthening technique (a study may use several); (d) cross-section shape

4. Experimental studies

Table 1 summarises the experimental column studies, the items examined and their main conclusions. The following subsections synthesise each group and appraise it critically.

4.1. FRP-jacket confinement

Confinement studies established the factors that limit jacket efficiency. Square sections are confined much less effectively than circular ones, and adding layers is far more beneficial in circular columns (Mirmiran et al., 1998). Effectiveness increases with corner radius (Rochette & Labossière, 2000; Al-Salloum, 2007; Wang & Wu, 2008; Li et al., 2019) and with section curvilinearization, while it decreases with aspect ratio (Zeng, Teng, Lin & Li, 2021); sharp-cornered sections gain almost nothing (Wang & Wu, 2008). Eccentricity and the associated strain gradient reduce the confinement benefit (Parvin & Wang, 2001; Lin, Zeng, Teng & Li, 2020), slenderness diminishes it further (Fitzwilliam & Bisby, 2010), and large-scale columns reach about 94% of the strength of small cylinders (Zeng, Lin, Teng & Li, 2018b). Fibre orientation (Au & Buyukozturk, 2005; Vincent & Ozbakkaloglu, 2013), partial wrapping (Zeng, Guo, Li & Chen, 2018a; Hemzah, Alyhya & Hassan, 2021), corner strip–batten detailing (Mostofinejad & Ilia, 2014), preloading and prestressing (Cheng & Yang, 2017), high-strength concrete (Hassan, Hodhod, Hilal & Bahnasaway, 2017) and seismic retrofitting (Memon & Sheikh, 2005; Galal, Arafa & Ghobarah, 2005; Del Zoppo, Di Ludovico, Balsamo, Prota & Manfredi, 2017) were also examined. Critically, every condition under which jacketing loses efficiency (rectangular sections, eccentricity, slenderness and flexural demand) is precisely the domain for which NSM and hybrid systems were proposed.

4.2. Longitudinal EBR and grooving methods

Longitudinal sheets bonded externally tend to buckle and debond under compression. Issa, Alrousan and Issa (2009) found that unconfined longitudinal fibres are ineffective, but when wrapped by hoops they are about half as effective as transverse fibres. In slender columns, longitudinal fibres restrained by hoops increased capacity by 65–77% for two sheets and a further 27–40% for four (Siddiqui, Alsayed, Al-Salloum, Iqbal & Abbas, 2014). Mostofinejad and Moshiri (2015) measured compressive strengths of CFRP, GFRP and AFRP equal to 78%, 55% and 20% of their tensile strength. EBR and in-situ NSM sheets gave negligible gains (1–5%), whereas grooving methods (EBROG, EBRIG), first developed to delay debonding in beams (Mostofinejad & Mahmoudabadi, 2010; Mostofinejad & Shameli, 2013), raised capacity by 14–18% by providing lateral support to the sheets (Moshiri, Hosseini & Mostofinejad, 2015). EBROG was also superior under eccentric load and its benefit grew with slenderness (Mostofinejad & Torabian, 2016; Noroozolyaee & Mostofinejad, 2019), and EBRIOG outperformed EBRIG (Saljoughian & Mostofinejad, 2020). Longitudinal sheets anchored into the footing with FRP anchors increased flexural capacity under cyclic load (Vrettos, Kefala & Triantafillou, 2013; del Rey Castillo, Griffith & Ingham, 2018), and combinations of longitudinal and transverse sheets changed shear to flexural failure in short columns (Kargaran & Kheyroddin, 2020a; Hassan et al., 2017; Al-Salloum, Al-Amri, Siddiqui, Almusallam & Abbas, 2018). These studies show that longitudinal FRP can carry compression only if buckling is prevented, which is the main rationale for embedding the reinforcement in grooves (NSM) and confining it (hybrid).

4.3. NSM and hybrid columns under cyclic lateral load

In seismic tests, cantilever columns are subjected to constant axial load and increasing cyclic lateral displacement. Barros, Varma, Sena-Cruz and Azevedo (2008) obtained gains of 75.8% and 25.1% for columns with 4Ø10 and 4Ø12 bars, showing that NSM is most effective in lightly reinforced columns, but energy dissipation hardly improved. Bournas and Triantafillou (2009) reported gains of 64%, 26% and 22% for stainless steel, CFRP strips and GFRP bars, respectively; a local end jacket was essential and cement mortar reduced effectiveness by about one third. Increasing the NSM ratio raised strength but reduced ductility, which the jacket restored (Sarafraz & Danesh, 2010; Olivova & Bilcik, 2009); hybrid strengthening raised capacity by up to 50%, but a very low concrete strength (8 MPa) prevented steel yielding and limited energy dissipation, which improved markedly with 29 MPa concrete (Perrone, Barros & Aprile, 2009). BFRP systems showed pinching and only 16% gain with NSM alone, but improved strength and ductility in hybrid form (Ding, Wu, Yang & Wu, 2013). In shear-critical short columns, NSM alone did not prevent shear failure, whereas hybrid schemes achieved up to 2.48 times the control capacity and higher energy dissipation (Haji, Naderpour & Kheyroddin, 2019; Kargaran & Kheyroddin, 2020b). Anchorage of the bars in the footing, filler type and end confinement therefore govern the seismic efficiency of NSM, yet only eight studies with about 60 specimens are available, and the effects of axial load ratio and bar type remain poorly quantified.

4.4. NSM and hybrid columns under axial, eccentric and flexural loading

Under concentric compression, NSM alone produced small gains of 5–9% (Chellapandian, Prakash & Sharma, 2017; Shayanfar et al., 2024a), partly because unrestrained strips buckled, whereas jackets and hybrid systems gave 20.9% and 25.5% (Chellapandian et al., 2017). The effect of eccentricity was clarified by tests that covered several points of the P–M diagram (Chellapandian & Prakash, 2019a; Chellapandian, Prakash & Sharma, 2019a): as the eccentricity ratio increased from 0 to 0.63, the NSM gain rose from 8% to 39.7% (85% in pure bending), the jacket gain fell from 20.9% to 7.2% (2% in bending), and the hybrid gain rose from 25.6% to 51.4%. Similar trends were reported for plain concrete with high-modulus laminates (Khorramian & Sadeghian, 2019), for biaxial bending (El-Maaddawy & El-Dieb, 2011) and for hybrid columns with eccentricity ratios up to 0.75 (Abokwiek, Abdalla, Hawileh & El Maaddawy, 2021). In slender columns jacketing was inefficient, and the advantage of NSM over EBR grew with slenderness (Gajdosova & Bilcik, 2013); hybrid strengthening also remained efficient at section aspect ratios up to 3 (Rao & Prakash, 2021). Conversely, Gopal, Krishnachandran and Bharatkumar (2020) observed no strength gain with NSM alone but a 25% gain with the hybrid system. Transverse NSM ropes outperformed EBR wraps (Obaidat, Ashteyat & Alfaris, 2020), and full-length longitudinal plus transverse NSM strips performed best in preloaded columns (Obaidat, Barham & Attar, 2021).

The database compiled by Afzali et al. (2025) contains 112 tests on unstrengthened, NSM-, jacket- and hybrid-strengthened columns from 13 sources (Chellapandian & Prakash, 2019b; Chellapandian, Prakash & Sharma, 2019c; Balla, Prakash & Rajagopal, 2023), most of them under concentric or eccentric compression (Fig. 5(a)). From matched control–strengthened pairs of these sources, supplemented by plain-concrete and pure-bending tests, 72 capacity ratios were computed (Fig. 5(b)). The mean ratio for NSM increases from 1.06 under concentric load to 1.18 for $e/h > 0.3$ and 1.40 in pure bending, with scatter caused mainly by buckling or debonding of unrestrained bars. Jackets show the reverse trend (1.20 to 1.02). The hybrid technique gives the largest and most consistent gains along the whole diagram (mean 1.30, 1.40, 1.53 and 1.63 for $e/h = 0$, ≤ 0.3, > 0.3

and pure bending), because the jacket confines the concrete, restrains the NSM bars against buckling and limits crack opening and bond deterioration.

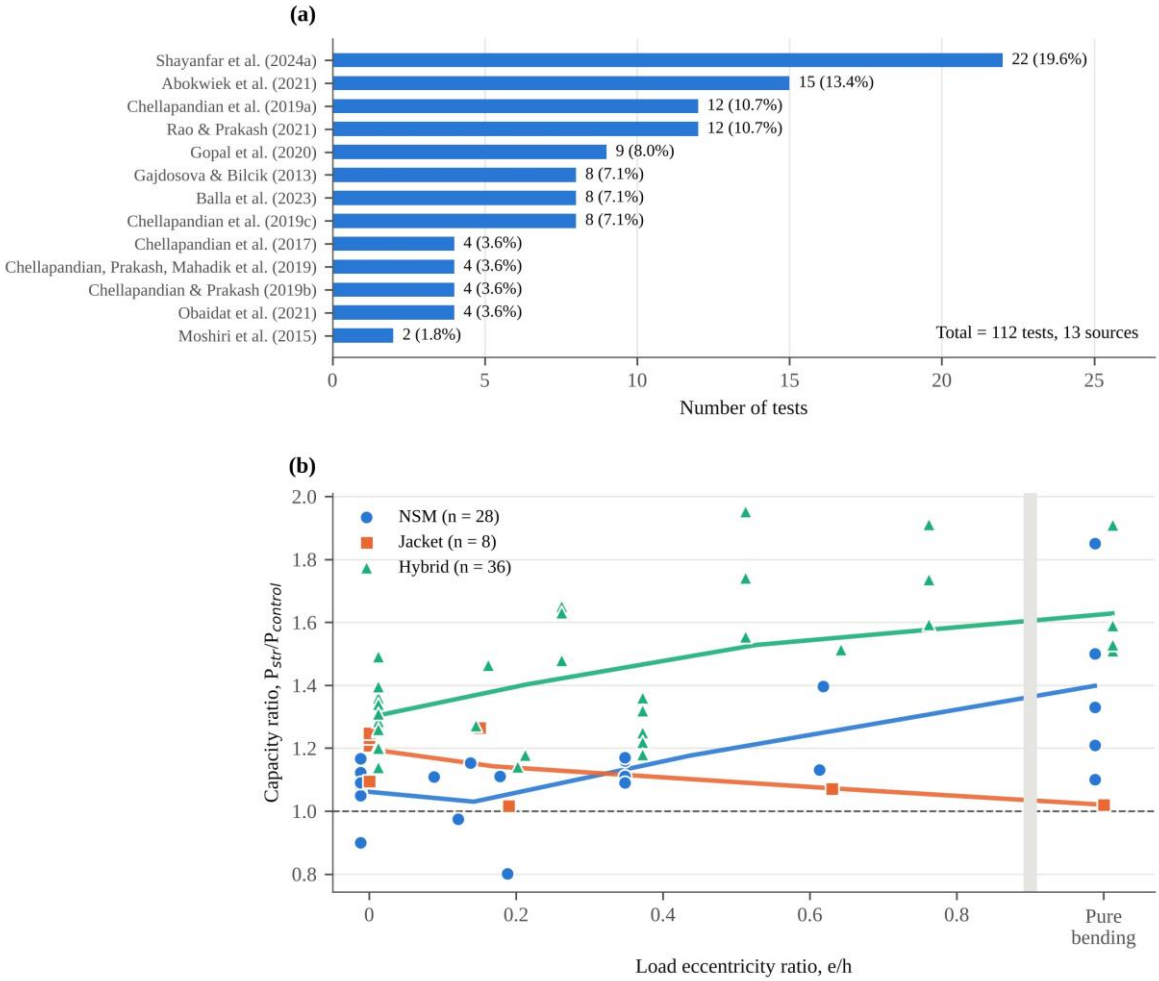

Fig. 5. Experimental evidence on NSM and hybrid columns: (a) number of tests per source in the 112-test database of Afzali et al. (2025); (b) capacity ratio of strengthened to control columns versus load eccentricity ratio, computed from Gajdosova and Bilcik (2013), Chellapandian et al. (2017, 2019a), Moshiri et al. (2015), Gopal et al. (2020), Obaidat et al. (2021), Abokwiek et al. (2021), Rao and Prakash (2021), Khorramian and Sadeghian (2019) and Shayanfar et al. (2024a, 2024c); lines join the mean values in each eccentricity range.

Most of these studies varied only the strengthening technique and the eccentricity. The authors' previous studies (Shayanfar et al., 2024a; Shayanfar et al., 2024c) therefore varied the number and material of the NSM bars, the number and material of the jacket layers and the groove size on identical specimens tested at points A, B and C (Fig. 6). NSM alone increased capacity by 5–9%, 9–17% and 10–50% at the three points, and hybrid strengthening by 14–34%, 18–36% and 51–91%. Doubling the groove width increased capacity and ductility through better stress transfer, GFRP bars were a cost-effective alternative to CFRP, and a third jacket layer added only 9% in bending because the jacket acts there by delaying crack opening rather than by confinement. Ductility increased by up to 197% under eccentric load, whereas in bending NSM alone reduced

displacement ductility. Failure of hybrid columns involved concrete crushing and jacket rupture, with debonding or rupture of some CFRP bars and intact GFRP bars (Fig. 7).

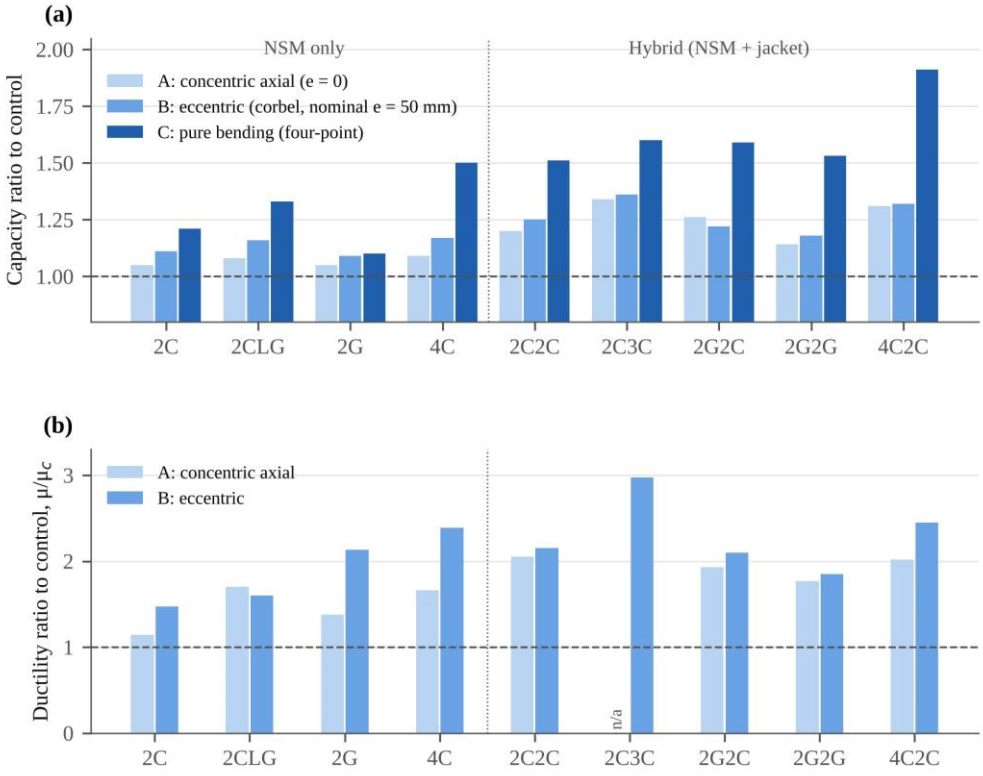

Fig. 6. Results of the authors' previous studies at the three key points of the P–M diagram: (a) capacity ratio; (b) ductility ratio (axial and eccentric tests). Specimen codes give the number and material of NSM bars (C: carbon, G: glass), followed by the number and material of jacket layers; LG denotes the larger groove. Data from Shayanfar et al. (2024a, 2024c).

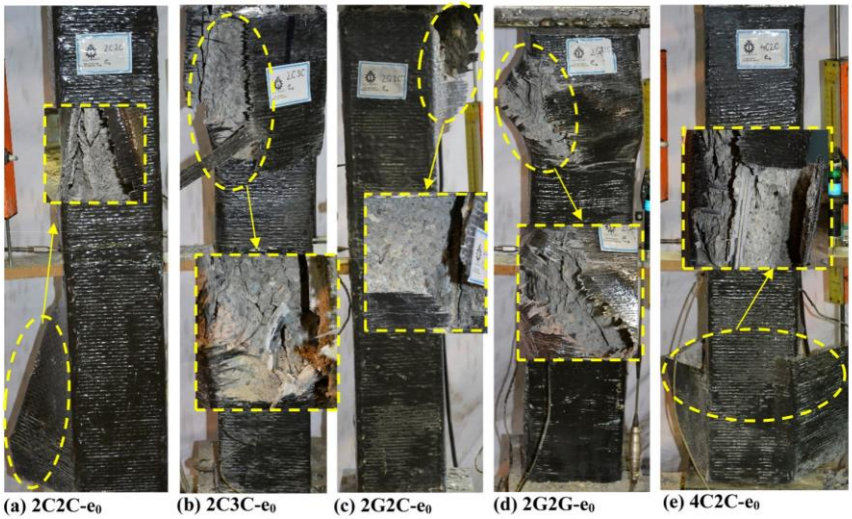

Fig. 7. Typical failure modes of hybrid-strengthened columns under concentric compression (Shayanfar et al., 2024a).

4.5. Repair of damaged columns

Hybrid systems were also effective for rapid repair. Earthquake-damaged bridge columns repaired with NSM BFRP bars and BFRP jackets recovered their strength, stiffness and ductility, without bar buckling or bond failure (Jiang, Zeng, Shen & Xu, 2016). Severely damaged columns repaired with rapid-set mortar and NSM bars recovered about 80% of their strength, whereas hybrid repair exceeded the original capacity (Jain, Chellapandian & Prakash, 2017) and restored capacity at all load paths, NSM alone being effective only when flexure dominated (Chellapandian & Prakash, 2018; Chellapandian, Prakash & Sharma, 2019b). After fire damage, strength and ductility were restored but axial stiffness was not (Chinthapalli, Chellapandian, Agarwal & Prakash, 2020).

Table 1. Summary of experimental studies on FRP-strengthened RC columns (grouped by sub-category)

No.	Study	Specimens (n; section; size, mm)	Loading	Items examined	Main conclusions
J – FRP-jacket confinement					
1	Mirmiran et al. (1998)	49; Square/Circular; 152.5×305 (L/D 2–5)	Axial (monotonic)	Section shape; jacket thickness (6, 10, 14 layers); length (L/D = 2–5); interface bond	Confinement far less effective in square than circular sections; number of layers strongly affects circular but not square columns; L/D = 2–5 had no marked effect.
2	Rochette & Labossière (2000)	Square/Rectangular/Circular; Model columns	Axial (monotonic)	Confinement stiffness (CFRP 3–5 layers; AFRP 3–12 layers); corner radius; fibre type	Extra CFRP layers gave a small strength gain but large ductility gain; confinement effectiveness increased with corner radius.
3	Parvin & Wang (2001)	9; Square; 108×108×305	Eccentric (e/h = 0, 0.07, 0.14)	Small eccentricities; jacket layers (0, 1, 2)	Jackets remained effective under small eccentricity, proportional to thickness, but the strain gradient reduced confinement efficiency.
4	Memon & Sheikh (2005)	Square; Large scale	Constant axial + cyclic lateral	GFRP layers; damage level; axial load level	More GFRP layers improved hysteretic response; more damaged or more heavily loaded columns required more layers.
5	Au & Buyukozturk (2005)	Circular; Cylinders	Axial (monotonic)	Fibre orientation (hoop, hoop + axial, ±45°); ply mix	Two response types around a "kinking point"; stiffer hoop jackets raised kinking stress and post-kinking stiffness.
6	Galal et al. (2005)	8; Square; Short columns	Constant axial + cyclic lateral	Anchored CFRP/GFRP	Anchored jackets increased ductility

				jackets; anchor bolts; layers	and energy dissipation (+25%); anchored CFRP with extra end confinement recommended for short columns.
7	Al-Salloum (2007)	20; Square/Circular; —	Axial (monotonic)	Corner radius (sharp, 1/6, 1/4, 1/3 of side)	Confinement increased with corner radius; an analytical strength model for square and circular sections proposed.
8	Wang & Wu (2008)	108; Square; 150×150×300	Axial (monotonic)	Corner radius (0–75 mm); f'c (30, 50 MPa); CFRP layers (0–2)	Strength rose with layers and corner radius; sharp-cornered sections gained negligible confinement; confinement less effective for higher-grade concrete.
9	Vincent & Ozbakkaloglu (2013)	24; Circular; —	Axial (monotonic)	Fibre angle (45°, 60°, 75°); end condition; jacket vs tube; f'c (50, 80 MPa)	45° and 60° fibres were least effective; end condition and jacket/tube type had minor influence.
10	Mostofinejad & Ilia (2014)	16; Square; 133×133×500	Axial (monotonic)	Corner strip–batten technique; wraps; continuous vs intermittent longitudinal corner strips; layers	Corner strips plus wraps/battens performed best; intermittent longitudinal strips outperformed continuous strips, which debonded.
11	Hassan et al. (2017)	8; Square; Large scale; HSC 59–120 MPa	Eccentric (uniaxial)	Full vs partial GFRP wrap; 1–2 longitudinal tension-face layers	Full wraps limited stiffness degradation; two tension-face layers produced more brittle, compression-controlled failure.
12	Cheng & Yang (2017)	11; Circular; —	Axial (monotonic)	Preloading; prestressed CFRP sheets; number of layers	Prestressed sheets gave higher gains and offset the adverse effect of preloading.
13	Del Zoppo et al. (2017)	7; Square; Short, heavily reinforced	Constant axial + cyclic lateral	FRP ratio; f'c (low vs normal)	FRP ratio of 0.34% prevented brittle shear failure of low-strength columns; two layers gave fully plastic deformation.
14	Zeng et al. (2018a)	15; Circular; —	Axial (monotonic)	Strip width; clear spacing; strip thickness	Peak load increased with strip width/thickness; second-branch slope insensitive to width; ultimate strain

					governed by FRP volumetric ratio.
15	Zeng et al. (2018b)	Rectangular; Large scale	Axial (monotonic)	Corner radius; jacket thickness	Bilinear stress–strain response; large-scale strength about 0.94 of small standard specimens.
16	de Diego et al. (2019)	Square; —	Axial (monotonic)	Jacket ultimate strain; corner radius; kε	Jacket rupture strain increased with corner radius; modified strain-efficiency factor proposed.
17	Li et al. (2019)	Square; Prisms	Axial (monotonic)	Corner radius (0–45 mm); predamage level; layers (2, 3)	Corner radius strongly affected strength of repaired prisms; confinement model including damage proposed.
18	Lin et al. (2020)	8; Rectangular; Large scale	Eccentric	Eccentricity; bending axis; jacket thickness	Capacity fell with eccentricity; existing confined-concrete models erred significantly in ductility under eccentric loading.
19	Zeng et al. (2021)	8; Rectangular/Square; 1000–1300 high	Axial (monotonic)	Section curvilinearization (r/s = 1/10–1/20); corner radius (25–65 mm); aspect ratio	Curvilinearization and larger corner radius markedly increased second-branch slope; aspect ratio governs confinement.
20	Hemzah et al. (2021)	Various; Damaged SCC	Axial (monotonic)	Full vs partial jackets on damaged columns; section shape	Full jackets gave larger strength recovery than partial wrapping.
L – Longitudinal EBR and grooving methods					
21	Issa et al. (2009)	55; Circular; Short	Axial (monotonic)	CFRP layers; fibre orientation; f'c; size	Unconfined longitudinal fibres negligible; when wrapped by hoops they were ~50% as effective as hoop fibres; size effect stronger for low f'c.
22	Fitzwilliam & Bisby (2010)	18; Circular; Small scale, varied L	Eccentric	Slenderness; eccentricity; hoop layers; longitudinal FRP	Slenderness reduced confinement benefit; four longitudinal FRP layers let a slenderness-35 column reach the capacity of a slenderness-10 column.
23	Vrettos et al. (2013)	4; Square; Large scale	Constant axial + cyclic lateral	Longitudinal sheets with	Flexural capacity increased almost

				carbon-fibre anchors; number/weight of anchors	linearly with anchors; fewer, heavier anchors more efficient.
24	Siddiqui et al. (2014)	12; Circular; Ø150; L = 600–1200	Eccentric (e = 25 mm)	Slenderness; 2 or 4 longitudinal sheets + 1 hoop layer	Longitudinal fibres became dominant after yielding in slender columns if laterally restrained; gains 65–77% (0→2 sheets) and 27–40% (2→4).
25	Mostofinejad & Moshiri (2015)	22; Circular; Ø150×500	Axial (monotonic)	Technique; FRP concentration; intermittent wraps; layers; epoxy-only grooves	Compressive strength of CFRP/GFRP/AFRP ≈ 78/55/20% of tensile; EBR and in-situ NSM ≈ 3% gain, grooving methods significantly higher; epoxy-only grooves negligible.
26	Moshiri et al. (2015)	10; Square/Circular; 133×133 and Ø150; 500	Axial (monotonic)	Strengthening technique; section shape	EBR (1–2.6%) and NSM (3–4.8%) gave marginal gains; EBRIG/EBROG 14–18% by delaying sheet buckling.
No.	**Study**	**Specimens (n; section; size, mm)**	**Loading**	**Items examined**	**Main conclusions**
27	Mostofinejad & Torabian (2016)	Circular; —	Eccentric	EBR vs EBROG under eccentric load	EBROG improved the contribution of longitudinal CFRP compared with conventional EBR.
28	Al-Salloum et al. (2018)	24; Circular/Square; Slender	Cyclic axial compression	1 hoop layer vs 2 longitudinal + 1 hoop layer; section shape	Longitudinal fibres contributed in tension, more in square sections; schemes equally effective under monotonic and cyclic loading.
29	del Rey Castillo et al. (2018)	5; Square; —	Constant axial + cyclic lateral	Longitudinal sheets with FRP anchors	Flexural strength increased; analytical flexural-capacity model proposed.
30	Noroozolyaee & Mostofinejad (2019)	9; Circular; Ø130; L = 500–900	Eccentric	Slenderness; EBR vs EBROG	EBROG outperformed EBR in all groups; EBROG gain increased with slenderness while EBR gain stayed constant.
31	Saljoughian & Mostofinejad (2020)	12; Square; 150×150×900	Cyclic axial compression	Longitudinal EBRIG/EBRIOG; corner strips; wraps/battens	Longitudinal sheets failed by buckling/debonding; EBRIOG better than EBRIG; mean FRP

					compressive stress 51.5% and 64.1% of coupon tensile strength.
32	Kargaran & Kheyroddin (2020a)	5; Square; Short	Constant axial + cyclic lateral	Full/intermittent jackets; corner strips; longitudinal and diagonal sheets	Retrofits shifted failure from diagonal shear to flexure; combined horizontal/vertical strips gave shear–flexure mode.

5. Finite element, analytical and numerical studies

Table 2 summarises the modelling studies. Their distribution over time and the basis of their validation are shown in Fig. 8.

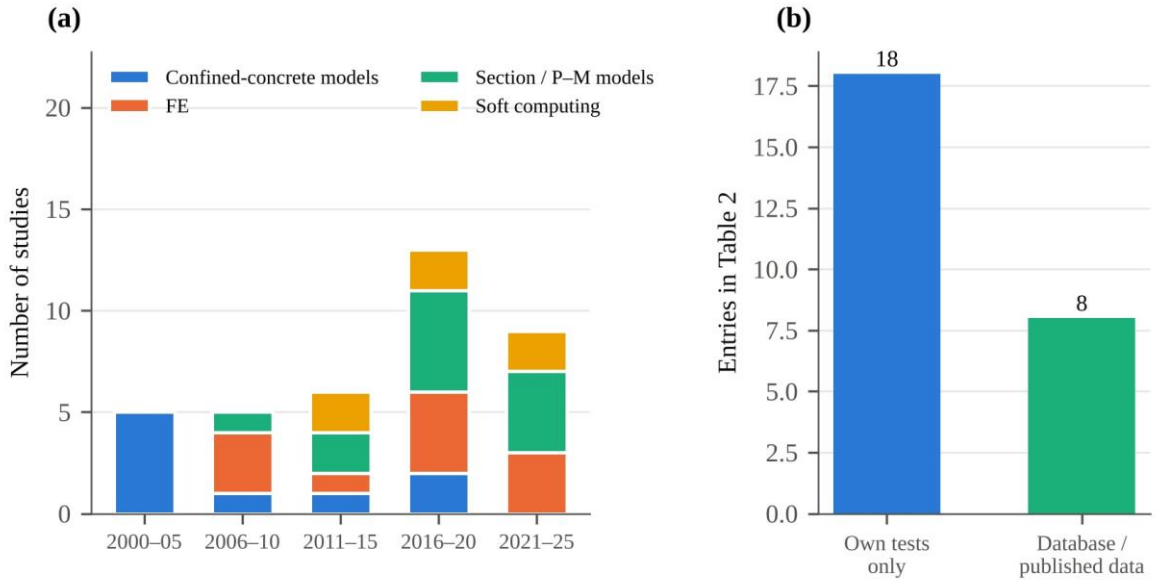

Fig. 8. Modelling studies: (a) number of studies by type and period; (b) basis of validation of the entries in Table 2.

5.1. Finite element modelling

Three-dimensional FE models of strengthened columns generally combine the concrete damaged plasticity (CDP) model for concrete, a confined stress–strain law (often that of Lam and Teng (2003a)) for jacketed concrete, bilinear or trilinear steel laws, linear-elastic FRP with a softening branch, and solid, shell and truss elements for concrete, jacket and bars. The adhesive can be modelled as a separate solid with interactions (Echeverria & Perera, 2013) or only through an interface law (Afzali et al., 2021). FE models have reproduced the response of NSM, jacketed and hybrid columns (Barros et al., 2008; Olivova & Bilcik, 2009; Chellapandian, Prakash, Mahadik & Sharma, 2019), extended test series through parametric studies (Issa et al., 2009; Cheng & Yang, 2017), and supported the interpretation of partial wrapping and damaged columns (Zeng et al., 2018a; Hemzah et al., 2021; Kargaran & Kheyroddin, 2020a). The model of Shayanfar et al. (2024a) predicted 22 tests with a mean FE-to-test ratio of 1.03 and a coefficient of variation of 4.1% (Fig. 9) and revealed that the stiff corbels used to apply eccentricity transmitted a smaller eccentricity than intended: removing them reduced the predicted capacity by up to 35% at e = 50 mm.

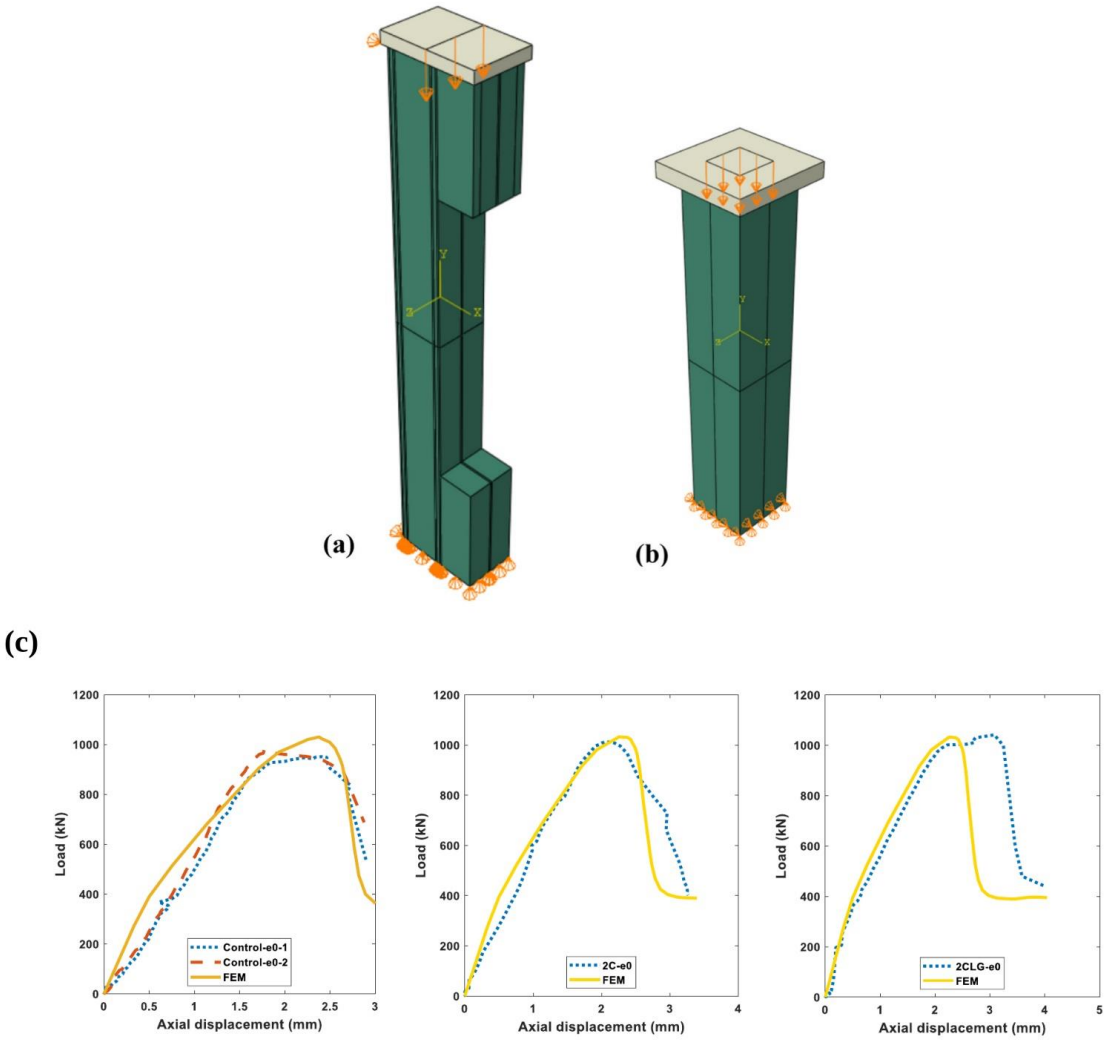

Fig. 9. FE modelling of NSM and hybrid columns: load application in (a) the eccentric and (b) the concentric models; (c) comparison of experimental and FE axial load–displacement curves. Adapted from Shayanfar et al. (2024a).

Critically, perfect bond is usually assumed between NSM bars and concrete in compression, buckling of bars and adhesive splitting are rarely represented, and 18 of the 26 modelling entries in Table 2 were validated only against the authors' own tests (Fig. 8(b)). Blind predictions and validation against independent databases are needed before FE models can be used to extend the limited test evidence.

5.2. Analytical models

Analytical work has two strands. Confined-concrete models for circular and rectangular sections (Chaallal, Hassan & Shahawy, 2003; Lam & Teng, 2003a; Lam & Teng, 2003b; Yang, Wei, Nanni & Dharani, 2004) were assessed against 720 tests by Ozbakkaloglu et al. (2013), who found design-oriented models more accurate than analysis-oriented ones and the Lam–Teng model the best; refinements address corner radius, predamage and jacket strain efficiency (Al-Salloum, 2007; Li et al., 2019; de Diego, Arteaga & Fernández, 2019). Section models based on equilibrium and strain compatibility predict the capacity of NSM and hybrid columns (Sarafraz & Danesh, 2010; El-Maaddawy & El-Dieb, 2011; Gajdosova & Bilcik, 2013; Khorramian & Sadeghian, 2019; Abokwiek et al., 2021; Obaidat et al., 2021; del Rey Castillo et al., 2018).

Chellapandian and Prakash (2019a) showed that including the compressive contribution of NSM bars improves accuracy. Code-based calculations (ACI Committee 318, 2019; ACI Committee 440, 2017) neglecting this contribution were conservative, with predicted-to-test ratios of 0.67–0.81 under concentric and 0.26–0.39 under eccentric load (Shayanfar et al., 2024a). A moment–curvature model using the Kent–Park (Scott) and Lam–Teng laws, an FRP compressive modulus of 0.80–0.85 times the tensile value and a bond-limited NSM strain cap of 0.0036–0.016, depending on bar number, groove size, bar surface and jacketing, predicted the bending tests within 6% (Shayanfar et al., 2024c). Because eccentric cases require iterative solutions and bond parameters are calibrated per test series, the generality of these models remains limited.

5.3. Soft-computing models

Soft computing, notably fuzzy logic (Zadeh, 1978), has been used to predict confinement effects (Cevik, 2011; Doran, Yetilmezsoy & Murtazaoglu, 2015) and NSM bond capacity (Nasrollahzadeh & Afzali, 2019; Naderpour, Mirrashid & Nagai, 2020). For columns, Shayanfar et al. (2024b) compiled 74 tests on NSM and hybrid columns, of which 24 were incomplete, and proposed a Takagi–Sugeno–Kang fuzzy model built by subtractive clustering (Chiu, 1994) that admits incomplete data, reducing the coefficient of variation from 23.5% to 13.6% and the mean absolute percentage error (MAPE) from 12.8% to 6.1%; the model indicated that capacity first rises and then falls as NSM axial rigidity increases. Ensemble learners (gradient boosting and random forest) tuned by metaheuristic algorithms and trained on 112 tests augmented by 112 synthetic samples reduced the MAPE to 12.0%, compared with 34.2% for an ACI 440.2R-based model, and SHAP analysis ranked section height and eccentricity as the most influential inputs and jacket parameters above NSM parameters (Afzali et al., 2025). Fig. 10 compares the errors of the different approaches. Although the datasets differ, the comparison shows that neglecting NSM compression is the dominant source of error in code-based predictions, while data-driven models are limited by small, heterogeneous and incompletely reported databases, and they should not be used outside their training domain.

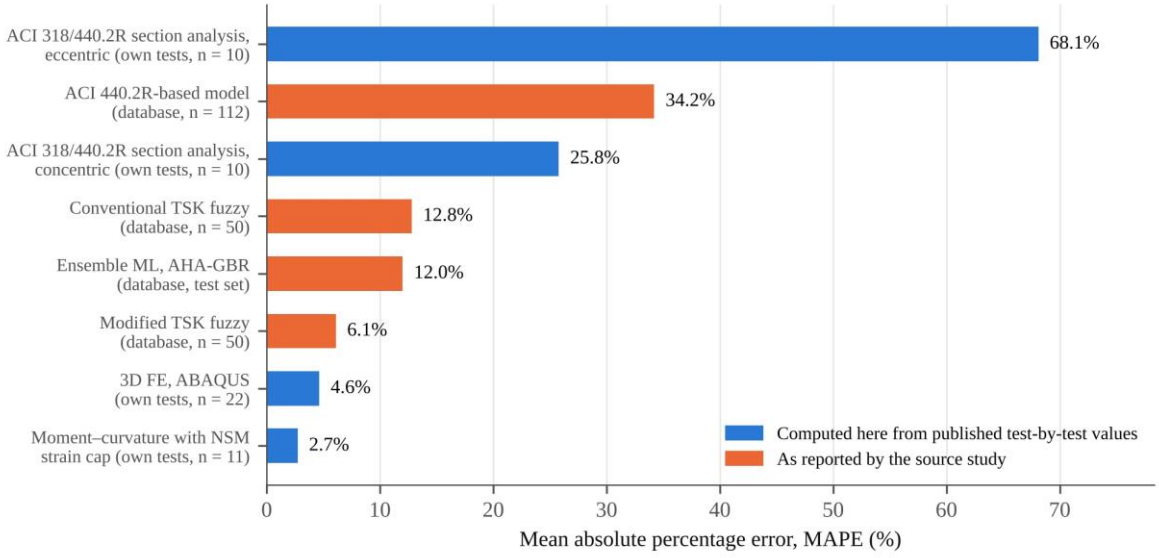

Fig. 10. Mean absolute percentage error of capacity predictions by different approaches (values computed in this review from published test-by-test results or reported by the source studies; datasets differ).

Table 2. Summary of FE, analytical and soft-computing studies.

No.	Study	Approach / tool	Items examined / modelling features	Data used for validation	Main conclusions
Finite element models					
1	Barros et al. (2008)	Nonlinear FE	NSM CFRP strips; cyclic column response	Own tests (12 columns)	Numerical model captured the lateral load–drift response and the effect of steel ratio.
2	Olivova & Bilcik (2009)	Nonlinear FE	NSM/jacket/hybrid columns under cyclic lateral load	Own tests	Acceptable prediction of the test response.
3	Issa et al. (2009)	FE parametric	CFRP layers, fibre orientation, f'c, size	55 own tests	Extended test findings; diminishing return of CFRP volumetric ratio.
4	Echeverria & Perera (2013)	3D nonlinear FE	Beam bond tests of NSM FRP rods; interface laws	Beam bond tests	Adhesive can be modelled as a separate solid or as an interface.
5	Cheng & Yang (2017)	FE parametric	Preloading, prestress level and layers of CFRP sheets	11 own tests	Preloading harmful, prestressing beneficial; more layers increased strength.
6	Zeng et al. (2018a)	3D FE	Partial FRP strips; arching action	15 own tests	3D model developed alongside tests to interpret arching action between strips.
7	Chellapandian, Prakash, Mahadik, & Sharma (2019)	FE	Hybrid columns under high eccentric compression	Own tests	Confirmed hybrid efficiency at high eccentricity.
8	Kargaran & Kheyroddin (2020a)	Numerical (FE)	Short columns with jackets/longitudinal sheets	5 own tests	Numerical simulation used alongside tests to interpret the retrofit schemes.
9	Afzali et al. (2021)	ABAQUS 3D	NSM strip–concrete bond; trilinear FRP law; CDP concrete; adhesive as interface behaviour	Published bond tests	Bond-slip behaviour of NSM strips reproduced; basis of column modelling assumptions.
10	Hemzah et al. (2021)	FE	Damaged SCC columns with full/partial jackets	Own tests	Validated model; full jackets more effective.
11	Shayanfar et al. (2024a)	ABAQUS (CDP; Lam–Teng confined concrete)	NSM/hybrid columns; corbel-based eccentricity; load position	22 own tests; PFEM/Pexp ≈ 0.92–1.10	Corbel removal cut capacity up to 35% at e = 50 mm, i.e. corbels transmit less than the nominal eccentricity.

Confined-concrete and section (analytical) models					
12	Chaallal et al. (2003); Lam & Teng (2003a, 2003b); Yang et al. (2004)	Confinement models	Stress–strain of FRP-confined circular/rectangular concrete; shape factors	Test databases	Lam–Teng design-oriented model adopted by ACI 440.2R-17.
13	Sarafraz & Danesh (2010)	Strain compatibility	Flexural capacity of NSM/hybrid columns	5 own tests	Good agreement with tests.
14	El-Maaddawy & El-Dieb (2011)	Section analysis	Biaxial bending capacity of hybrid columns	9 own tests	Model for biaxially loaded strengthened columns.
15	De Lorenzis & Tepfers (2003); Ozbakkaloglu et al. (2013)	Model assessment	88 confinement models; 720 circular tests	Database	Design-oriented models more accurate than analysis-oriented ones; Lam–Teng best.
16	Gajdosova & Bilcik (2013)	Analytical + parametric	Slenderness, steel ratio	8 own tests	Benefit of NSM over EBR grows with slenderness.
17	Al-Salloum (2007); Li et al. (2019); de Diego et al. (2019)	Confinement models	Corner radius, predamage, jacket strain efficiency	Own tests	Shape- and damage-dependent confinement and kε expressions.
18	Khorramian & Sadeghian (2019)	Analytical + parametric	NSM ratio, f'c	14 own tests	NSM compressive strain rises with NSM ratio and f'c.
19	Chellapandian & Prakash (2019a); Chellapandian et al. (2019a, 2019b)	Strain compatibility	P–M curves with/without NSM compression; damaged columns	Own tests	Including NSM compression improves accuracy.
20	del Rey Castillo et al. (2018); Obaidat et al. (2021); Abokwiek et al. (2021)	Capacity models	Flexural/axial capacity of longitudinally strengthened columns	Own tests	Reasonable agreement within each test series.
21	Shayanfar et al. (2024a)	ACI 318-19 / ACI 440.2R-17 section analysis	Code capacity, NSM compression ignored	22 own tests	Conservative: PACI/Pexp = 0.67–0.81 (axial) and 0.26–0.39 (eccentric).
22	Shayanfar et al. (2024c)	Moment–curvature (Kent–Park/Scott; Lam–Teng)	NSM strain cap ε_max (0.0036–0.016) for bond; FRP compressive modulus 0.80–0.85 Et	11 own tests; Pu ratio 0.94–1.04	Bond-related strain cap is essential; depends on bar number, groove size, surface and jacket.
Soft-computing models					
23	Cevik (2011); Doran et al. (2015)	Soft computing / fuzzy logic	Strength gain and confinement coefficient of FRP-wrapped columns	Databases	Accurate alternative to empirical

					confinement models.
24	Nasrollahzadeh & Afzali (2019); Naderpour et al. (2020)	Fuzzy (Sugeno, Mamdani); ANFIS	NSM FRP bond capacity	Pull-out databases	Satisfactory accuracy compared with analytical bond models.
25	Shayanfar et al. (2024b)	Modified TSK fuzzy (subtractive clustering)	Inputs Ag f'c, Ast fy, AF EF, nJ tJ EJ, e/h; incomplete data	74 tests (50 complete)	Using incomplete data cut CoV from 23.5% to 13.6%; capacity peaks then falls as AF EF increases.
26	Afzali et al. (2025)	GBR/RFR + AHA/AOA/SMA; TGAN; SHAP	14 inputs; synthetic augmentation	112 tests + 112 synthetic	MAPE 12.0% vs 34.2% for ACI 440.2R-based model; e/h and jacket parameters most influential; NSM efficiency drops for f'c > 38 MPa.

6. Critical discussion and research needs

The comparison of the reviewed studies reveals several issues that limit the transfer of their findings into design (Fig. 11).

- Inconsistent definitions. Capacity gains are referred to different controls, and ductility is defined from axial, lateral or mid-span displacements with different failure criteria (e.g. 20% post-peak drop), so that ductility gains cannot be compared across studies.
- Load application. Eccentricity has been applied through corbels, steel caps with knife edges or rollers. FE evidence that corbels transmit less than the nominal eccentricity (Shayanfar et al., 2024a) suggests that some eccentric results are biased; the eccentricity actually transmitted should be measured or calibrated.
- Neglected variables. Groove geometry, bar surface treatment, filler type and bar spacing, which govern bond in pull-out and beam tests (Sharaky et al., 2013a; Sharaky et al., 2013b), were varied in very few column studies.
- NSM in compression. Compressive strength and modulus of FRP bars, buckling inside the groove and the bond–slip law under compression are not characterised, which explains the conservatism of code-based calculations.
- Scale, slenderness and load history. Most specimens are small; slender, biaxially loaded and large-scale columns, sustained loads, cyclic hybrid response, durability and fire are scarcely studied.
- Modelling practice. FE and analytical models are mostly calibrated on their own tests, and data-driven models depend on incomplete public data. An open, fully documented database of NSM and hybrid column tests is the most effective step towards reliable models and code provisions for tension-controlled columns.

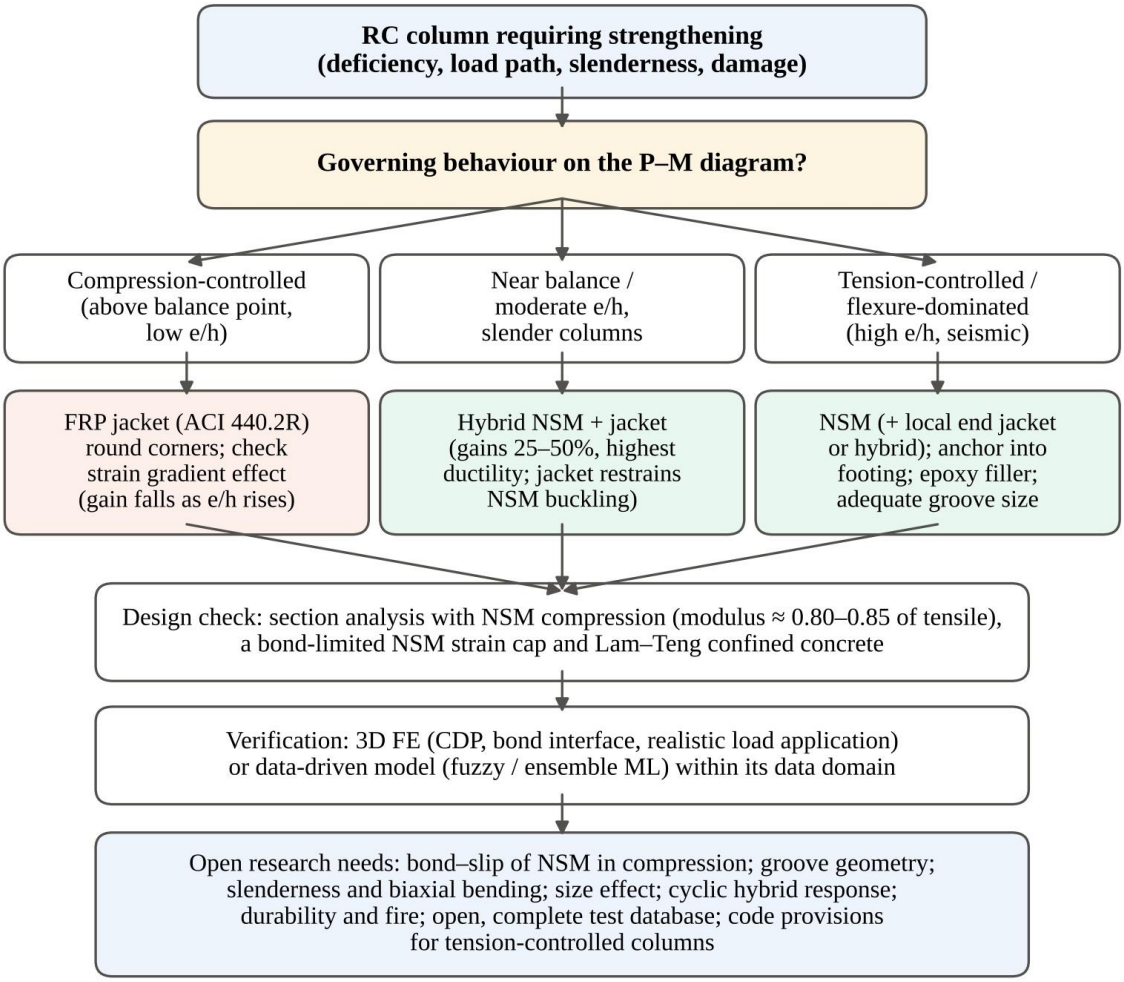

Fig. 11. Framework synthesised from the review for selecting and verifying FRP strengthening of RC columns, and the related research needs.

7. Conclusions

This review analysed 100 documents on FRP strengthening of RC columns, with emphasis on NSM and hybrid techniques. The main conclusions are:

- The literature is dominated by small square specimens under concentric compression; only a handful of studies cover the full P–M diagram, pure bending, slenderness or cyclic loading of hybrid systems.
- NSM strengthening becomes more effective as flexure dominates (mean capacity ratio 1.06 concentric, 1.40 in bending), jacketing shows the opposite trend, and hybrid strengthening gives the largest gains (mean 1.30–1.63) and ductility because the jacket confines the concrete and restrains the NSM bars.
- Anchorage, end confinement, adhesive type, groove size, bar material and the existing steel ratio strongly influence NSM efficiency; larger grooves and GFRP bars are promising, cost-effective options.
- Code-based section analysis ignoring NSM compression and jacket effects in tension-controlled columns is markedly conservative; models that include NSM compression and a bond-limited NSM

strain, calibrated FE models and fuzzy or ensemble-learning models reduce the prediction error to about 3–13%.

- Future work should standardise test protocols, quantify NSM behaviour in compression, investigate slender, large-scale and cyclically loaded hybrid columns, and build an open database to support validated models and design provisions.

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