

END ANCHORAGE OF EXTERNALLY BONDED LAMINATES: REVIEW

ENDVERANKERUNG VON AUF OBERFLÄCHEN AUFGEKLEBTEN CFK-LAMELLEN: LITERATURÜBERSICHT

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SUMMARY

Carbon fiber reinforced polymer (CFRP) laminates find extensive application in construction, especially for concrete repair and structural modifications. Application of externally bonded reinforcement (EBR) often suffers debonding due to the limited tensile strength of near-surface concrete, leading to bond failure (zipper effect). To prevent this kind of failure and ensure load transfer at the laminate ends, mechanical end anchorages are typically used. This publication summarises studies conducted using externally bonded reinforcement applied to concrete surfaces and studies using end anchoring. It presents the amount of output data that could enable future analysis of the stiffness of reinforcement systems and discusses the challenges of integrating studies conducted at the local level in order to accurately represent behaviour at the global structural level.

ZUSAMMENFASSUNG

Kohlefaserverstärkte Polymerlaminat (CFK) finden breite Anwendung im Bauwesen, insbesondere bei der Betonsanierung, mit strukturellen Änderungen. Bei der Verwendung von aufgeklebten Lamellen kommt es aufgrund der begrenzten Zugfestigkeit der oberflächennahen Betonschichten häufig zu einer Ablösung der Lamelle, was zu einem vollständigen Versagen des Verbundes führt (Reißverschlusseffekt). Um diese Art von Versagen zu verhindern und die Lastübertragung an den Lamellenenden sicherzustellen, bieten mechanische Endverankerungen die erforderliche Kraftübertragung. Diese Veröffentlichung fasst Studien zusammen, die mit auf Betonoberflächen aufgeklebten Lamellen und mit Endverankerungen durchgeführt wurden. Sie präsentiert die Menge an Ausgangsdaten, die eine zukünftige Analyse der Steifigkeit von Verstärkungssystemen ermöglichen

könnten, und diskutiert die Herausforderungen bei der Integration von Studien, die auf lokaler Ebene durchgeführt wurden, um das Verhalten auf globaler Strukturebene genau abzubilden.

1. INTRODUCTION

1.1 Motivation and application areas

The reinforcement of concrete components with carbon fiber reinforced polymer (CFRP) is an established method for increasing the durability and load-bearing capacity of structures. It is particularly used for the reinforcement of beams in bending and shear, as well as for the strengthening of columns, and represents a technically sophisticated as well as economically advantageous solution [1].

Concrete structures can be reinforced with CFRP laminates for a variety of reasons. These include concrete rehabilitation, changes to the structural system or changes in use, for example when traffic or service loads need to be increased. Components can also be strengthened if, due to errors in design, implementation planning or construction, a smaller reinforcement cross-section was installed than structurally necessary or required to limit crack widths [2].

1.2 Advantages and limitations

CFRP laminates offer several advantages over other reinforcement methods, including high tensile strength, corrosion resistance and aesthetics. They are easy to handle and lightweight, meaning that the reinforcement has only a minimal impact on the existing structure [1-2].

There are also some limitations to the use of CFRP laminates despite the advantages mentioned above. They exhibit brittle material behaviour, are sensitive to transverse pressure and transverse impact, they are expensive and there is a risk of mechanical damage, for example through drilling. The reinforcement system is temperature-sensitive and may be used at component temperatures of up to 50 °C in the laminate area. At high temperatures, the adhesive loses its strength, and the CFRP laminates can no longer be considered structurally effective. Direct exposure to sunlight can also cause heating and thus impair the adhesive strength. Permanent or alternating moisture penetration can also have a negative effect on the reinforcement system. In such cases, additional protective action must be taken [1-2].

1.3 Problem statement and aim of this review paper

A considerable amount of research has been conducted at the global level, i.e., over the entire span of the beam, demonstrating the effectiveness of the developed strengthening systems. In contrast, only limited studies have focused on local level, where “local” refers to the zone at the beam ends in which the anchorage of the strengthening laminate is provided. The objective of local experiments is to understand the bond and anchorage behaviour of EBR laminates. The measurements in the local experiments are focussed on evaluation of efficiency of the connection between EBR and concrete.

A key difficulty lies in the fact that there is no standardized method to reliably assess and correlate the behaviour of strengthening systems in the local zone as well as at the global structural level. This makes it challenging to evaluate and compare the effectiveness of different end anchoring systems for externally bonded reinforcement using CFRP laminates in reinforced concrete structures. Therefore, it is crucial to identify appropriate indicators and criteria that allow for consistent assessment across both local and global levels, enabling meaningful comparison of various anchorage solutions.

For the purposes of this study, the load-bearing capacity and stiffness of the anchors are taken as the primary criteria for comparing the strengthening systems. In literature, the amount of available information about the evaluation of stiffness varies considerably.

2. TECHNICAL BACKGROUND

2.1 Strengthening methods and bond behaviour

Strengthening of structural elements with bonded reinforcement can be carried out using either near-surface mounted (NSM) systems or externally bonded reinforcement (EBR). These two methods differ significantly in their bond behaviour and load-transfer mechanisms. Near surface mounted CFRP laminates provide significantly better bond performance compared to externally bonded ones. By bonding the laminate within grooves, a defined bond length can be achieved, allowing the laminate to develop its maximum stress. In addition, NSM laminates enable high force transfer even with relatively short anchorage lengths. Although the transferred force decreases slightly after a certain length, it is still possible to ensure targeted force absorption with a specific anchorage length. The bond

strength in near surface mounted reinforcement results from the minimum bond stress between concrete and adhesive [3].

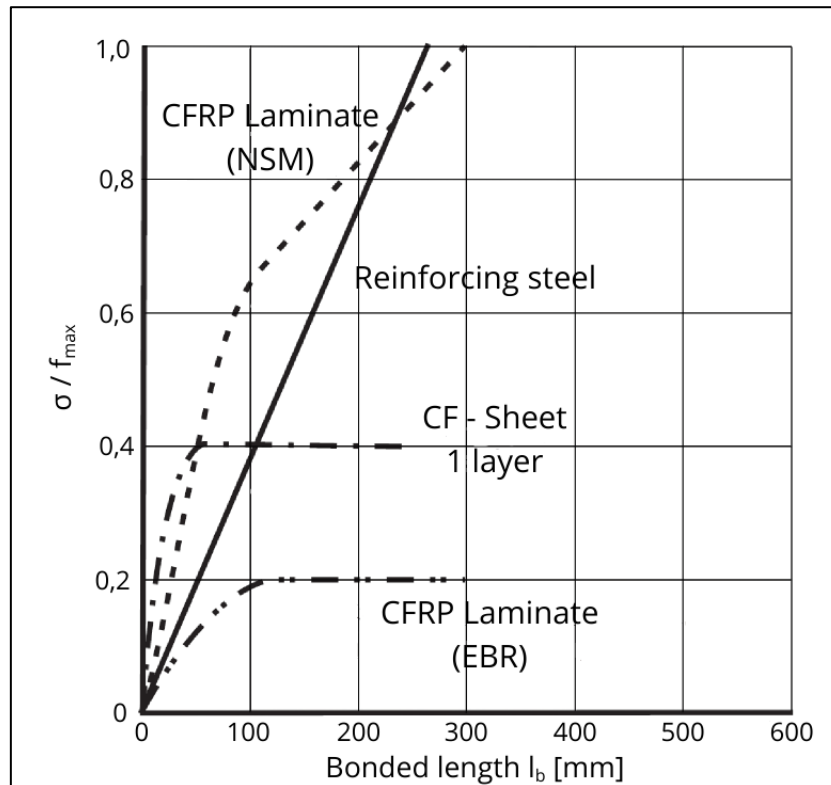


Fig. 1: Development of relative axial stress of the different application methods [3]

In the case of EBR, the transferable stress remains limited. Externally bonded reinforcement has a lower bond strength, which is characterised by the low tensile strength of concrete layers close to the surface. Due to the moderate tensile strength of these layers, the released forces cannot be redistributed, causing a so-called zipper effect. Once a crack forms, the concrete cover can no longer resist these stresses, and local debonding of the EBR laminate occurs. Because the bond capacity around a single crack is very limited, the debonding cannot be confined to a small region. Instead, it typically propagates along the laminate, leading to a complete bond failure.

The anchorable tensile force of bonded reinforcement at an end anchorage compared to other reinforcement with similar maximum tensile force is shown in Fig. 1. The figure clearly shows that the bond stress increases up to a certain point, which is defined by the maximum effective bond length of the bonded reinforcement. Beyond this point, the curve in the diagram levels off, and the force does not exceed a relative tensile stress ratio of 20% [1, 3].

2.2 Need for mechanical end anchorages

At the ends of the CFRP laminates, the force must be transferred to the adjacent component via an anchorage. Various suggestions are presented and discussed in the technical literature. The load-bearing capacity and stiffness of the anchorages serve as the primary criteria for their comparison. Within the scope of the approval requirements for bonded reinforcement, it must be ensured that failure occurs primarily in the free length area and not at the anchorage. Accordingly, the anchorage must be designed in such a way that it guarantees at least the full theoretical load-bearing capacity of the cross-section [4].

Given the limitation on bond development in case of EBR, end anchorages are typically used to develop the ultimate strength of the laminates. A review of different end anchorage systems and their efficiency to develop axial stresses in CFRP reinforcement are discussed in [4]. It is reported that clamping the laminates using pretensioned bolts (as seen in Fig. 2) allows for the development of the full tensile capacity of the laminates. An ideal end anchorage requires that failure occurs primarily due to laminate rupture and the slip in the end anchorage is practically zero. Hence, the end anchorage must be designed to guarantee at least the full theoretical load-bearing capacity of the laminate cross-section [4].



Fig. 2: End anchorage of CFRP EBR using plates clamped together through bolt pretension [4]

2.3 Prestressing of CFRP laminates

One of the strengthening methods involve prestressing CFRP laminates. Approximately 60% of the tensile strength of the CFRP is utilized, enabling the structural element to achieve its maximum reinforcement potential with full use of the composite material. When the load reaches 70%, debonding of the laminate occurs, causing a sudden failure of the element without prior delamination. Prestressing

the CFRP increases the ultimate load capacity of the element and raises the load level at which initial cracking appears. It also reduces crack widths, promotes a more uniform crack distribution, and allows for better exploitation of the CFRP's material properties, with strain values approaching the ultimate limit [5]. However, prestressing is a relatively time-consuming technique. This underlines the need for alternative approaches that combine ease of application with high effectiveness.

3. CLASSIFICATION OF AVAILABLE STUDIES

A wide range of experimental investigations has been carried out on reinforced concrete members strengthened with externally bonded CFRP laminates, employing different strengthening methods. The strengthening systems by using externally bonded reinforcement were systematically divided into local and global level and further subdivided into three categories:

1. Strengthening solely by bonding

The CFRP strip is reinforced to the concrete with possible preliminary surface preparation by roughening or by using a solvent cleaning. The glued laminate joint is partially rigid, resulting in slippage that leads to premature debonding and failure.

2. Strengthening solely by end anchorages

The anchoring systems are fastened to the reinforced concrete beams, which were strengthened using CFRP strips anchored to the concrete. The strips are secured solely by means of mechanical anchorages, without adhesive bonding. In this configuration, the CFRP strip act as an external tie, with the entire tensile force being transferred to the structure at discrete points corresponding to the anchorage locations.

3. Strengthening by use of bonded reinforcement with end anchorages

The CFRP laminate is bonded to the concrete surface and additionally anchored externally at the ends of the strip. The implementation of effective anchorage systems enhances the ultimate load capacity and results in a more ductile and predictable failure pattern. Using anchorages changes the failure mode towards a more ductile response, meaning that the structural element retains its load-bearing capacity even after the CFRP laminate has debonded from the concrete [5].

In the literature review, individual tests were analysed and assigned to the appropriate category. The available data and the possible gaps, were then visualised in Table 2 in order to enable their analysis and evaluation in order to define the stiffness of the reinforcement system used. For this purpose, the available data was divided into a four-level classification scale which was represented in the Table 1 by different shades, as shown below:

Table 1: Classification scale for the amount of data in the literature

0-25 %	25-50%	50-75%	75-100%
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Table 2: Classification of the CFRP strengthening systems

	Only Bond	Only End Anchorage	Bond and End Anchorage
Lokal Level	K. Benzarti [6] C. Czaderski [7]		L. Correira [8] J. P. Firmo [9]
	J. P. Firmo [9]		J. P. Firmo [9]
	N. Houhou [10]		
	J. Li [11]		J. Sena-Cruz [12]
	H. Wilmes [13]		
Global Level	M. Breveglieri [14]		L. Correira [15]
	C. Czaderski [7]		
	Narmashiri [16]		
	B. Piątek [17]		B. Piątek [17]
	C. Pellegrino [18]		C. Pellegrino [18]
	Al-Ridha [19]		Al-Ridha [19]
	Yang Et Al. [20]	Yang Et Al. [20]	Yang Et Al. [20]

Classification of data from the literature showed that there is a surprising amount of data that has been classified either into the (0-25%) or (75-100%) category. This means that the data assigned to the (75-100%) category provides a basis for analysing the stiffness of reinforcement systems and for a possible or potential assessment of the behaviour of systems in the local and global zones.

Based on Table 2, it can be seen that a relatively large number of literature items have been assigned to the (0-25%) category in strengthening systems using only bonding, mainly in the local zone. The global zone shows a slightly larger amount

of output data for evaluation, but this is due to the fact that most of the research on reinforced concrete was carried out in the global zone, while the local zone is mainly represented by tests in which the influence of the environment on the bonded CFRP laminates was examined.

Table 2 clearly shows the small amount of data or even its absence in systems that reinforce only by anchoring the laminate at the ends, without bonding it to the concrete surface. This indicates the need for further research using this system of strengthening reinforced structures. Only one literature reference in the global zone has been assigned to this category. However, these studies have provided a detailed analysis of this type of reinforcement and a large amount of initial data for further evaluation.

Reinforcement using bonded reinforcement with end anchoring shows a large amount of data assigned to the category (75-100%), on the basis of which the stiffness of the reinforcement systems can be determined. However, as in the case of reinforcement solely by bonding laminate to the concrete surface, the tests that were carried out in the local area were mainly conducted to determine the behaviour under environmental conditions, rather than to examine the reinforcement system itself.

4. INFLUENCING FACTORS FOR EBR CONNECTIONS

4.1 *Activation mechanism of end anchorages*

In the case of bonded EBR laminates, a significantly small proportion of the ultimate strength of the laminates is utilised. This is because, the failure occurs due to shear failure in the cover concrete, which is limited by the concrete tensile capacity. Hence, the modern high strength bonded adhesive systems cannot be exploited for this type of connection [3].

In addition to bonding of laminates, end anchorage systems are required to develop the ultimate capacity of the laminates in the strengthening solutions. End anchorages have little influence on the performance of the connection up to the point of CFRP debonding. After the debonding, the end anchorages are activated and transfer the force between the laminate and concrete. This effect is clearly seen in Fig. 3. The tests show that debonding of the EBR is observed at about 20% of the rupture strength of the CFRP. Until the debonding, the measured stiffness based on the front, middle and rear slip are comparable. This implies that as long

as the bond between laminate and the concrete is active, a higher stiffness of the connection is available. Once the debonding occurs, the stiffness measurements based on front slip are significantly higher than that based on rear slip. This is based on the elasticity modulus of the CFRP laminates which is typically lower than reinforcing steel. No reduction in stiffness measurements based on the rear end slip as seen in Fig. 3 is an indication of an ideal end anchorage system. The influence of stiffness of the EBR connections is reflected in the limitation of crack formation in the reinforced beams. The reinforced beams also show a higher ultimate load capacity and a slight increase in stiffness, i.e. a reduction in deflection and cracking [17-18].

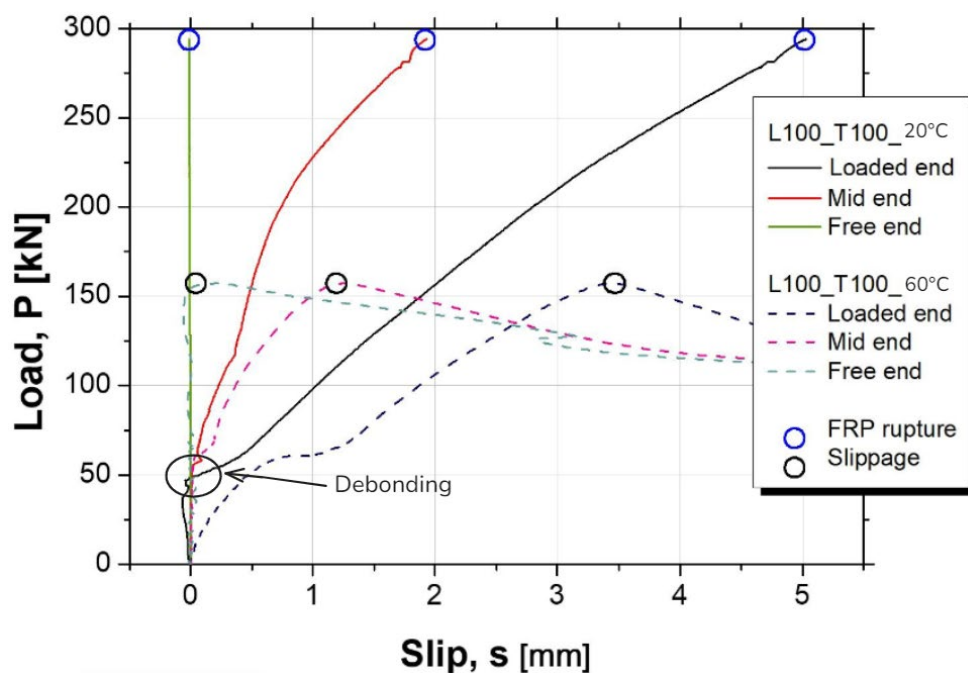


Fig. 3: Load slip behaviour of bonded + end anchored connection at different temperatures [12]

4.2 Influence of temperature

The end anchorage of EBR laminates using plates clamped by pretensioned bolts provide development of the ultimate strength of the laminates at ambient temperature. This may not necessarily be true for higher temperature. As seen in Fig. 3, for a temperature of 60°C, the ultimate strength of the laminates could not be developed. The failure occurs because of slippage of laminate in the end anchorage zone. The thermal expansion results in reduced pre-tension in the bolts, thereby reducing the clamping force which is responsible for the end anchorage.

Thus, in case of clamped end anchorage system, the temperature plays a crucial role in the efficiency of the connection.

5. CONCLUSION

This publication shows, that a lot of studies with externally bonded reinforcement with CFRP laminates have been already done. Research conducted in the local zone has focused primarily on examining the impact of environmental conditions rather than the behaviour of the reinforcement system itself. In the global zone, the entire behaviour of reinforcement systems is examined, using full anchoring of the tapes, with or without end anchoring, together with the influence of the load force. The behaviour of reinforcement systems using CFRP strips is therefore much better examined in the global zone. Currently, there are no criteria for assessment on a local and global level that would allow the behaviour of the reinforcement system in the global zone to be assessed based solely on tests carried out in the local zone. This gap highlights the need for more experimental investigations at the local level, in order to define reliable indicators integrating local anchorage behaviour to global structural response.

REFERENCES

- [1] FINCKH, W.: *Verstärken von Betonbauteilen: Tragwerksplanung im Bestand*. Springer Fachmedien, Wiesbaden, 2024
- [2] WEIDNER, J., KÖHLER, W, KRAMS, J.: *Verstärken von Betonbauteilen mit geklebter Bewehrung. Bemessung und Ausführung*, Beton- Stahlbetonbau, Bd. 95, Nr. 9, S. 537–543, Sep. 2000
- [3] ZILCH, K., NIEDERMEIER, R., FINCKH, W.: *Sachstandbericht: Verstärken von Betonbauteilen mit geklebter Bewehrung*, DAfStb - Deutscher Ausschuss für Stahlbeton, Berlin, 2011
- [4] SCHLAICH, M., ZWINGMANN, B., LIU, Y., GOLLER, R.: *Zugelemente aus CFK und ihre Verankerungen*, Bautechnik, Bd. 89, Nr. 12, S. 841–850, Dez. 2012, doi: 10.1002/bate.201200057
- [5] PIĄTEK, B.: *Czynniki wpływające na pracę belki żelbetowej wzmocnionej sprężonymi taśmami CFRP*, Politechnika Rzeszowska, Rzeszów, 2015.

- [6] BENZARTI, K., CHATAIGNER, S., QUIERTANT, M., MARTY, C., AUBAGNAC, C.: *Accelerated ageing behaviour of the adhesive bond between concrete specimens and CFRP overlays*, *Constr. Build. Mater.*, Bd. 25, Nr. 2, S. 523–538, Feb. 2011, doi: 10.1016/j.conbuildmat.2010.08.003
- [7] CZADERSKI, C., BREVEGLIERI, M.: *Long-term behaviour of externally bonded reinforcement under sun radiation*, Report No. 701, Federal Roads Office, Bern, Switzerland, 2021
- [8] CORREIA, L., BARRIS, C., FRANCA, P., SENA-CRUZ, J.: *Effect of Temperature on Bond Behavior of Externally Bonded FRP Laminates with Mechanical End Anchorage*, *J. Compos. Constr.*, Bd. 23, Nr. 5, S. 04019036, Okt. 2019, doi: 10.1061/(ASCE)CC.1943-5614.0000961
- [9] FIRMO, J.P., CORREIA, J., R., PITTA, D., TIAGO, C., ARRUDA, M.R.T.: *Experimental characterization of the bond between externally bonded reinforcement (EBR) CFRP strips and concrete at elevated temperatures*, *Cem. Concr. Compos.*, Bd. 60, S. 44–54, Juli 2015, doi: 10.1016/j.cemconcomp.2015.02.008
- [10] HOUHOU, N., BENZARTI, K., QUIERTANT, M., CHATAIGNER, S., FLETY, A., MARTY, C.: *Analysis of the nonlinear creep behavior of concrete/FRP-bonded assemblies*, *J. Adhes. Sci. Technol.*, Bd. 28, Nr. 14–15, S. 1345–1366, Juli 2014, doi: 10.1080/01694243.2012.697387
- [11] LI, J., GRAVINA, R., VISINTIN, P., SMITH, S.T.: *Durability and Long-Term Performance of FRP-to-Concrete Joints under Environmental Conditioning: Experimental and Analytical Study*, *J. Compos. Constr.*, Bd. 24, Nr. 4, S. 04020021, Aug. 2020, doi: 10.1061/(ASCE)CC.1943-5614.0001023
- [12] SENA-CRUZ, J., CORREIA, L., BARRIS, C.: *Behaviour of metallic anchorage plates for prestressing CFRP laminates under room and elevated temperatures*, IABSE Conference, Kuala Lumpur 2018: Engineering the Developing World, Kuala Lumpur, Malaysia, 2018, S. 111–118. doi: 10.2749/kualalumpur.2018.0111
- [13] WILMES, H., KOLESNIKOV, B.: *CFK/Titan, ein Hybridwerkstoff zur verbesserten Kopplung von Faserverbundstrukturen*, *Intelligente Leichtbau Systeme*, Hannover, Deutschland, 2002

- [14] BREVEGLIERI, M., CZADERSKI, C.: *RC slabs strengthened with externally bonded CFRP strips under long-term environmental exposure and sustained loading. Part 2: Laboratory experiments*, Compos. Part C Open Access, Bd. 6, S. 100210, Okt. 2021, doi: 10.1016/j.jcomc.2021.100210
- [15] CORREIA, L., SENA-CRUZ, J., MICHELS, J., FRANCA, P., PEREIRA, E., ESCUSA, G.: *Durability of RC slabs strengthened with prestressed CFRP laminate strips under different environmental and loading conditions*, Compos. Part B Eng., Bd. 125, S. 71–88, Sep. 2017, doi: 10.1016/j.compositesb.2017.05.047
- [16] NARMASHIRI, K., RAMLI SULONG, N.H., JUMAAT, M.Z.: *Failure analysis and structural behaviour of CFRP strengthened steel I-beams*, Constr. Build. Mater., Bd. 30, S. 1–9, Mai 2012, doi: 10.1016/j.conbuildmat.2011.11.009
- [17] PIĄTEK, B., SIWOWSKI, T.: *Wpływ kotwienia mechanicznego taśm CFRP na efektywność wzmocnienia belek żelbetowych*, Inżynieria Bud., Bd. 12, S. 659–662, 2016
- [18] PELLEGRINO, C., MODENA, C.: *Flexural Strengthening of Real-Scale RC and PRC Beams with End-Anchored Pretensioned FRP Laminates*, ACI Struct. J., Bd. 106, Nr. 3, 2009, doi: 10.14359/56496
- [19] AL-RIDHA, A.S.D., MAHMOUD, K.SH., ATSHAN, A.F.: *Effect of carbon fiber reinforced polymer (CFRP) laminates on behaviour of flexural strength of steel beams with and without end anchorage plates*, Mater. Today Proc., Bd. 49, S. 2778–2785, 2022, doi: 10.1016/j.matpr.2021.09.313
- [20] YANG, D.-S., PARK, S.-K., NEALE, K.W.: *Flexural behaviour of reinforced concrete beams strengthened with prestressed carbon composites*, Compos. Struct., Bd. 88, Nr. 4, S. 497–508, Mai 2009, doi: 10.1016/j.compstruct.2008.05.016