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A Review on the Study of Bond Behavior between Reinforcement Thin Bars and Concrete

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***Abstract*-** The bond behavior is a mechanism that allows force transfer between reinforcement and concrete. A variety of factors affect the steel-concrete bond and, for their evaluation, the most common used tests are the pull-out test and the beam test. The study demonstrates the application of the ProKnow-C process (Knowledge Development Process-Constructivist) to enable the researcher to select a set of articles that provides knowledge about the theme. Using this process, 1597 articles were initially identified and, after a process of continuous selection, 6 aligned papers on the research theme were selected, demonstrating the relevance of these articles by bibliometric analysis. Subsequently, the systematic analysis was performed, using, in this case, five research lenses based on the tests used to study bond behavior in reinforced concrete and parameters related to the steel bars (e.g. anchorage length, diameter and surface conformation of the steel bars). The results of the systematic analysis demonstrated that: the majority of the researches does not approach the study of bond behavior using thin steel bars; only pull-out tests were used to evaluate the steel-concrete bond; and these tests commonly use ribbed bars and variable anchorage lengths. The use of the ProKnow-C provided knowledge about the research theme and made it possible to identify research opportunities.

Keywords*-Bond, Steel, Concrete, ProKnow-C, Bibliometric Analysis.*

I. INTRODUCTION

The bond strength between steel and concrete is a relevant mechanism which allows the use of reinforced concrete structures. This property is composed, schematically, of three parts: adhesion, friction and bearing action [1] [2].

The relationship between bond strength and the slip of the steel rebar demonstrates the bond behavior, which is associated with the load capacity and service load of reinforced concrete elements [3].

The most common methods used to determine steel-concrete bond are: pull-out tests and beam tests. The pull-out test, recommended by RILEM-CEB-FIP-RC6, consists of the extraction of a centralized steel bar in a concrete cubic test specimen using an equipment that applies a pull-out load progressively up to bond failure. The relative slip of the bar is measured using a displacement transducer [2]-[4].

The specimens used in beam tests are molded according to RILEM-CEB-FIP-RC5. Simple bending stresses are applied to the beam and displacement transducers positioned at the ends of the bar measure the slip of the bar to obtain the bond strength of the structural element [5].

Few studies about steel-concrete bond have been done using steel bars with diameters less than 10 mm and conventional concrete.

This paper proposes a review of the scientific literature with the aim to identify knowledge gaps that justify the relevance of the future research using ProKnow-C (Knowledge Development Process-Constructivist) [6].

Thus, the present study aims to: demonstrate a process of article selection for a bibliographic set; and analyze the selected papers identifying the research opportunities.

This paper is presented in five sections: introduction, selection of papers for the bibliographic set, bibliometric analysis, systematic analysis and conclusions.

II. SELECTION OF PAPERS FOR THE BIBLIOGRAPHIC SET

The process of selecting articles for theoretical reference composition adopted in this work was ProKnow-C (Knowledge Development Process-Constructivist) [6], a method developed for the selection and analysis of bibliographic references. This process was used in many papers in order to build knowledge in the researcher, enabling him to realize the research with stated theories [7] [8].

The selection of papers consists in procedures to filter the papers previously selected in order to create a set of articles that were aligned with the research theme and it was based on the stages: definition of the keywords of the search, conducting of a preliminary investigation and selection of papers that are aligned with the research theme [6].

First, the keywords of the search were defined. To the proposed theme, the study of bond behavior in reinforced concrete using two types of tests, the most relevant keywords

to the research were: bond, steel, concrete, pull-out test and beam test.

In the next stage, the database to the search was defined. Science Direct database, indexed by the CAPES website [9], was chosen because it has complete texts and it shows a great scientific recognition.

The next step is to define the first filters to be applied, which were: the date of publication (10 years before the date of the present research - 2006 to 2016) and the type of paper (complete text).

After these initial definitions, the search for the papers in the chosen database was done, obtaining 614 results for the first combination of keywords (*bond*, *steel*, *concrete* and *pull-out test*) and 983 results for the second combination (*bond*, *steel*, *concrete* and *beam test*), reaching a total of 1597 papers for the initial bibliographic set.

After the gross base papers were selected, the next step consisted of realize the adherence test of the keywords. For this test, two papers that were aligned with the theme were selected from the gross base papers. The keywords of these articles were compared to the keywords used in the search. No new keywords were identified in these two articles, so the selection stage of the papers for the gross base papers was considered as finished.

The next filters were based on the following aspects: redundancy (duplicate papers), papers with titles aligned to the research theme, scientific recognition, abstracts aligned with the research theme and full texts of the papers aligned with the research theme.

A. Redundancy

To organize the papers, the references were imported into the EndNote application [10], which allowed verifying that 105 articles were duplicated. These articles were excluded, obtaining a total of 1492 articles.

B. Papers with Titles Aligned to the Research Theme

After a new reading and analysis of the titles, it was verified that 1465 articles were related to composite materials, numerical models, analysis of cracking, temperature, corrosion and others themes. These articles were not aligned to the research aim, so they were excluded from the bibliographic set, which included 27 papers.

C. Scientific Recognition

The next filtering refers to the scientific recognition, in which it was analyzed how many citations each paper has presented since its publication, being this data obtained through Google Scholar [11] and ordered in a decreasing way. According to the Pareto Postulate, the most cited papers represent most of the scientific recognition, being used the value of 85% of the sum of the citations of all the papers [7]. However, the analysis of the papers' abstracts of the bibliographic set (27 papers) wouldn't represent great effort, so it was decided not to carry out this step.

D. Abstracts Aligned with the Research Theme

After reading the abstracts of the 27 selected papers, it was possible to identify 21 articles that were not aligned with the research theme. These papers were excluded, so the bibliographic set included 6 papers.

E. Full Texts of the Papers Aligned with the Research Theme

Finally, the full text of the selected papers was read, and the 6 papers were maintained due to the alignment of the full text with the research theme. The final bibliographic set is presented in Table I (in alphabetical order by the first author).

III. BIBLIOMETRIC ANALYSIS

The bibliometric analysis of the bibliographic set is based on statistical methods to analyze the publications. This analysis contains four stages: to determine the relevance of the journals, to determine the scientific recognition of the papers, to determine the relevance of the authors of the papers and to determine the most used keywords [6].

A. Relevance of the Journals

The first analysis aims to determine how many papers were published by each journal. The six papers selected for the bibliographic set were published by two journals. The journal "Construction and Building Materials" published five papers and the "International Journal of Adhesion & Adhesives" published one paper.

The second analysis demonstrated how many times the journals of the selected papers were referenced by the papers of the bibliographic set itself. The bibliometric analysis demonstrated that 110 references had been cited by the six selected papers in the bibliographic set. The most relevant journals are presented in Figure 1.

TABLE I. BIBLIOGRAPHIC SET

Bibliographic Set
Arel, H. S; Yazici, S. (2012) Concrete–reinforcement bond in different concrete classes. Construction and Building Materials, v.36, p.78-83.
Bouazaoui, L.; Li, A. (2008) Analysis of steel/concrete interfacial shear stress by means of pull out test. International Journal of Adhesion & Adhesives, v.28, p.101-108.
Garcia-Taengua, E.; Martí-Vargas, J. R.; Serna, P. (2016) Bond of reinforcing bars to steel fiber reinforced concrete. Construction and Building Materials, v.105, p.275-284.
Pop. I.; Schutter, G. De; Desnerck, P.; Onet, T. (2013) Bond between powder type self-compacting concrete and steel reinforcement. Construction and Building Materials, v.41, p.824-833.
Shen, D.; Shi, X.; Zhang, H.; Duan, X.; Jiang, G. (2016) Experimental study of early-age bond behavior between high strength concrete and steel bars using a pull-out test. Construction and Building Materials, v.113, p.653-663.
Valcuende, M.; Parra, C. (2009) Bond behavior of reinforcement in self-compacting concretes. Construction and Building Materials, v.23, p.162-170.

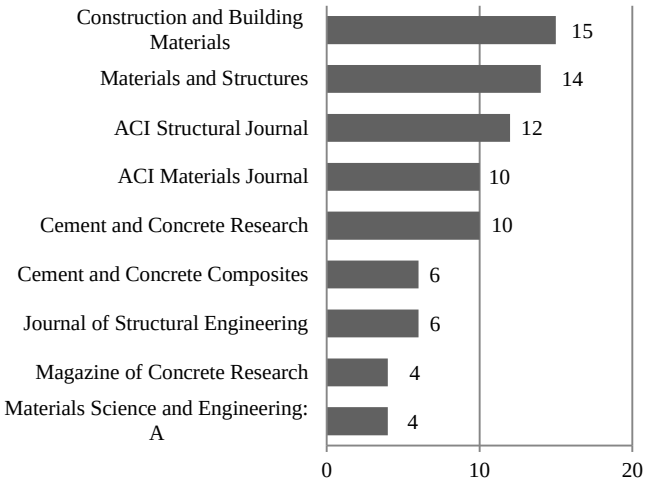

Figure 1. Relevance of the references in the bibliographic set.

B. *Scientific Recognition of the Papers*

The first analysis was based on the number of citations that each article has received since its publication, obtained through Google Scholar [11] (Figure 2). The most cited papers were "Bond behavior of reinforcement in self-compacting concretes" [12], with 72 citations, and "Analysis of steel/concrete interfacial shear stress by means of pull-out test" [13], with 32 citations.

In a second analysis, it is observed the rank of the set to which the journals belong, which is provided by CAPES [14]. This classification divides the publications into groups: A1, A2, B1, B2, B3, B4, B5 and C (in order of the highest rating group for those with zero weight). The papers of the bibliographic set were published by journals with A1 and A2 ranking, as demonstrated in Table II.

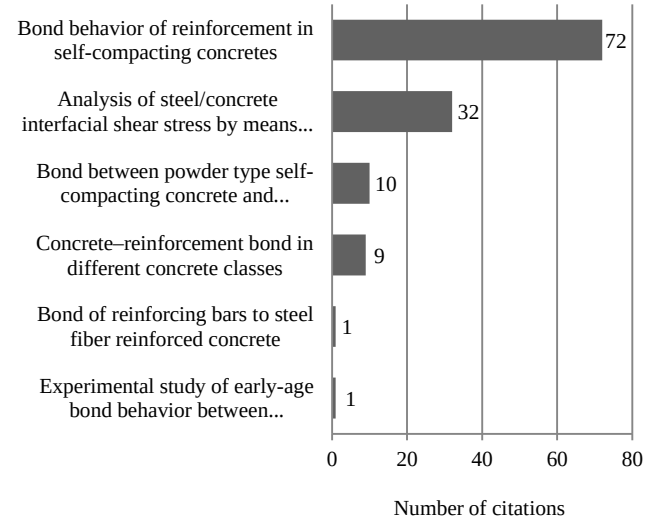

Figure 2. Relevance of papers according to scientific recognition.

TABLE II. JOURNALS CLASSIFICATION

Article	Journal	Degree
Valcuende, M.; Parra, C. (2009) [12]	Construction and Building Materials	A1
Bouazaoui, L.; Li, A. (2008) [13]	International Journal of Adhesion & Adhesives	A2
Arel, H. S; Yazici, S. (2012) [15]	Construction and Building Materials	A1
Shen, D.; Shi, X.; Zhang, H.; Duan, X.; Jiang, G. (2016) [16]	Construction and Building Materials	A1
Garcia-Taengua, E.; Martí-Vargas, J. R.; Serna, P. (2016) [17]	Construction and Building Materials	A1
Pop. I.; Schutter, G. De; Desnerck, P.; Onet, T. (2013) [18]	Construction and Building Materials	A1

C. *Relevance of the Authors of the Papers*

This stage identifies the relevance degree of the authors of the papers and considers the articles of the bibliographic set and the articles in the references. As illustrated in Figure 3, this analysis highlights the author Dejian Shen, who presents 9 published articles.

D. *Most Commonly used Keywords*

This step analyzed which keywords were most commonly used in the articles of the bibliographic set. This analysis demonstrated that 23 keywords were used 29 times. The most used were "concrete" and "bond strength". Analyzing the five keywords used for the database search, four of them were present in the keywords of the bibliographic set, which were: "bond", "concrete", "steel" and "pull-out test".

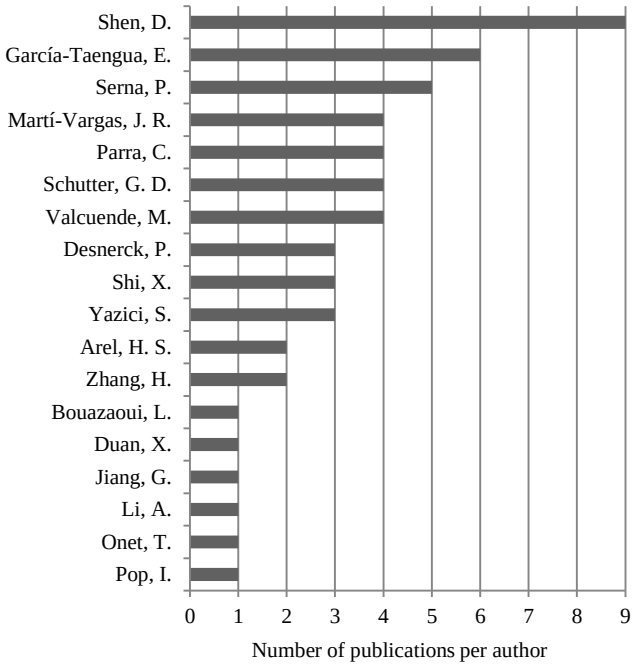

Figure 3. Relevance degree of the authors of the papers.

IV. SYSTEMATIC ANALYSIS

The systematic analysis proposed by ProKnow-C [6] aims to analyze selected papers (representative sample) according to the research lenses defined by the researchers with the intention of identifying the strengths and weaknesses of the papers, showing research opportunities [7].

This stage includes the following steps: definition of the criteria for the analysis; and evaluation of each article according to the adopted criteria. The research lenses are summarized in Table III.

A. Lens 1: Tests Used to Study Bond Behavior in Reinforced Concrete

The study of bond behavior in reinforced concrete elements could be realized using different tests. In all of the selected papers the steel-concrete bond was analyzed by pull-out tests. These tests were realized to study:

- the bond behavior between steel bars and conventional concrete or self-compacting concrete of different mix compositions [12];
- the quality of the bond strength on steel-concrete interface [13];
- the concrete–reinforcement bond strength in concretes with different compressive strength levels [15];
- the bond behavior between steel bars and high strength concrete of different ages [16];
- the effect of steel fibers on bond toughness parameters and on bond strength [17];
- the bond behavior between steel bars and self-compacting concrete or vibrated concrete [18].

To study steel-concrete bond, the most used tests were: pull-out tests, beam tests and confined bars tests. None of the papers portray beam tests and confined bars tests, so they should be used by future researches, in order to obtain results according to different tests for a better understanding about the theme.

TABLE III. RESEARCH LENSES

Lenses	
1	Tests used to study bond behavior in reinforced concrete
2	Comparison between the results of different tests
3	Diameter of the steel bars used in the tests
4	Surface conformation of the bars used in the tests
5	Anchorage length used in the tests

B. Lens 2: Comparison Between the Results of Different Tests

The comparison between the results obtained by different tests makes possible to verify if one of them is overestimating the data. Significant variations may indicate that the test may have not been performed properly.

All the papers use pull-out tests, so there are no results of different tests to compare.

Thus, future researches should portray the study of bond behavior using two or more types of tests, in order to compare the data and verify the coherence of the results.

C. Lens 3: Diameter of the Steel Bars Used in the Tests

Thin bars are normally used in reinforced concrete elements. There are various researches approaching the steel-concrete behavior, but few of them evaluated the reinforcement with steel bars of lower diameters (d <10mm).

Five papers of the bibliographic set [12] [13] [15] [16] [18] use steel bars with a diameter equal to or greater than 10 mm. Only one paper [17] uses thin bars (8 mm) between the various bars used in the tests. The diameters of the steel bars used in the pull-out tests are presented in Table IV.

Therefore, future researches should investigate the bond behavior using these bars of inferior diameters, which are widely used in the civil construction.

D. Lens 4: Surface Conformation of the Bars Used in the Tests

The literature agrees that the bond strength in ribbed bars is generally superior to the observed in smooth bars. Five articles of the bibliographic set [12] [15] [16] [17] [18] use ribbed bars. Only one article [13] uses bars which the initial state of the surface was smooth. However, these bars were treated by mechanical sandblasting to change the characteristics of the surface. Thus, future researches should investigate the use of bars with different surface conformations (smooth and ribbed), analyzing the values of the bond strength for both.

TABLE IV. DIAMETERS OF THE STEEL BARS

Articles	Diameters
Valcuende, M.; Parra, C. (2009) [12]	16 mm
Bouazaoui, L.; Li, A. (2008) [13]	12 mm, 16 mm, 20 mm
Arel, H. S; Yazici, S. (2012) [15]	14 mm
Shen, D.; Shi, X.; Zhang, H.; Duan, X.; Jiang, G. (2016) [16]	16 mm
Garcia-Taengua, E.; Martí-Vargas, J. R.; Serna, P. (2016) [17]	8 mm, 12 mm, 16 mm, 20 mm
Pop. I.; Schutter, G. De; Desnerck, P.; Onet, T. (2013) [18]	10 mm, 12 mm, 14 mm

E. Lens 5: Anchorage Length Used in the Tests

The specimens were built according to RILEM-CEB-FIP-RC6 [4], which establishes an anchorage length of five times the steel rebar diameter (5d).

However, some bibliographies indicate a high dispersion of the data, suggesting a better analysis of the anchorage length used in these tests.

Four articles [12] [15] [16] [17] use both the anchorage length recommended by RILEM. Two articles [13] [18] use variable anchorage lengths. The anchorage lengths used in the tests are presented in Table V. Future researches should demonstrate the real influence of this parameter on the steel-concrete bond.

V. CONCLUSIONS

The academic research provides knowledge to the researcher and allows a better understanding about the theme. The constructivist process (ProKnow-C) was used in order to create a bibliographic set of selected articles according to method criteria, resulting in a set of relevant papers on steel-concrete bond. The selected articles were analyzed with the aim to identify knowledge gaps and research opportunities.

In its first stage, the procedures of the process allowed the researcher to select from a gross set of 1597 papers, among which 6 most relevant papers were selected through a continuous process of filtering. These papers present title, abstract and full text aligned with the research aim.

The following step, bibliometric analysis, allowed the researchers to the identification of journals and authors who stood out in publications on the theme. The journal "Construction and Building Materials", which presented the largest number of papers in the bibliographic set and also papers in the references, and the journal "Materials and Structures", which also had a large number of publications, were highlighted. The analysis of the degree of relevance of the authors highlights Dejian Shen, which has the largest number of publications.

The results of the systematic analysis of the articles, the last step, demonstrated that the majority of the researches used the pull-out tests to evaluate the steel-concrete bond. Therefore, other tests should be realized for a better evaluation of this mechanism. It is concluded that future researches should investigate the bond behavior using thin steel bars (d <10mm) and bars with different surface conformations (smooth and ribbed). Furthermore, the anchorage length should be evaluated to expand the understanding about the influence of this parameter on the bond behavior.

Analyzing the results obtained in this study, it is concluded that all the objectives established at the beginning of this research were achieved. Therefore, the use of the constructivist process (ProKnow-C) was very adequate, contributing to future researches based on bond behavior between reinforcement thin bars and concrete.

TABLE V. ANCHORAGE LENGTHS

Articles	Anchorage length
Valcuende, M.; Parra, C. (2009) [12]	5d
Bouazaoui, L.; Li, A. (2008) [13]	Bars of d = 12mm → 100, 150, 200, 250 and 300 mm. Bars of d = 16mm and 20mm → 140, 210 and 280 mm.
Arel, H. S; Yazici, S. (2012) [15]	5d
Shen, D.; Shi, X.; Zhang, H.; Duan, X.; Jiang, G. (2016) [16]	5d
Garcia-Taengua, E.; Martí-Vargas, J. R.; Serna, P. (2016) [17]	5d
Pop. I.; Schutter, G. De; Desnerck, P.; Onet, T. (2013) [18]	3d, 4d and 5d

where: d = diameter of the steel bar.

Some limitations of this research are: the sample field made available by the database of CAPES, the adopted temporal filter (articles between 2006 and 2016) and the subjectivity of the process (the researchers will make a selection according to their knowledge and predilections).

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