Bond in Concrete 2012 – General Aspects of Bond J. W. Cairns, G. Metelli and G. A. Plizzari (eds)
2012 Publisher creations, ISBN: 978 - 88 - 907078 - 1 - 0

Japan concrete institute TC activities on bond behavior and constitutive laws in RC (Part 1: research survey on bond problems)

Y. Sato
Kyoto University, Kyoto, Japan

H. Shima
Kochi University of Technology, Kochi, Japan

T. Kanakubo
University of Tsukuba, Tsukuba, Japan

ABSTRACT: Literature on bond problems published in the United States of America, Germany, Austria, and Japan from the late 19th century to the early 21st century is surveyed. The history of bond research based on 345 papers selected from 11 journals published in the four countries is summarized.

1 SURVEYED LITERATURE

Literature on bond problems is surveyed as one of the activities of the Japan Concrete Institute Technical Committee on Bond Behavior and Constitutive Laws in Reinforced Concrete. The committee selected 345 papers from 11 journals published in the United States of America, Germany, Austria, and Japan from the late 19th century to the early 21st century. These papers mostly discuss on relationships between bond stress and slip although several papers deal with testing methods, analysis methods, and design guidelines. Table 1 is a summary of the surveyed journals.

Austria and Germany began to pioneer the research and development of reinforced concrete engineering when Matthias Koenen (1849-1924) initially proposed the flexural analysis method of RC beams in 1886 (Koenen 1886). The RC techniques were also quickly applied to large, high-rise structures in the USA. Supposedly, bond tests had been conducted by individual engineers beginning in the late 19th century although the first technical paper about bonds appeared in 1905.

Abrams, University of Illinois at Urbana, mentioned that Thaddeus Hyatt (1816-1901) conducted tests to determine the bonds between concrete and iron bars as early as 1876 (Abrams 1913). America and Germany still lead the world in RC investigations including bond research. Austria made important contributions as well, especially during the early periods of RC history. In addition, significant research activities were performed in Japan after the 1960s.

Table 1. Surveyed journals.

Abbreviation	Journal	Period	Country	Number of papers
ACI	Journal of the American Concrete Institute	1905-1986	USA	100
	Structural Journal of the ACI	1987-2010	USA	
ASCE	Transactions of the American Society of Civil Engineers	1872-1940	USA	89
	Proceedings, ASCE, Structural Division	1939-1982	USA	
	Journal of Structural Engineering, ASCE	1983-2010	USA	
AIV	Zeitschrift für Architektur und Ingenieurwesen	1901-1906	Germany	2
BS	Beton und Eisen	1905-1942	Germany	36
	Beton- und Stahlbetonbau	1943-1945 1950-1982		
BI	Bauingenieur	1920-1996	Germany	5
DAfStb	Deutscher Ausschuss für Eisenbeton	1911-1938	Germany	39
	Deutscher Ausschuss für Stahlbeton	1938-2005		
ÖIAZ	Zeitschrift des Österreichischen Ingenieur- und Architekten-Vereins	1859-1910	Austria	15
JSCE	Journal of the Japan Society of Civil Engineers	1933-2009	Japan	10
AIJ	Transactions of the Architectural Institute of Japan	1967-1984	Japan	12
	Journal of Structural and Construction Engineering	1985-2008		
JCIa	Proceedings of the Japan Concrete Institute	1983-2009	Japan	23
JCIb	Concrete Research and Technology	1982-2002	Japan	5
--	Other papers (listed in references)			9
Total				345

Early RC technical papers were contributed to general engineering journals or general civil engineering journals. Such papers were then contributed to RC journals, which were founded in the early 20th century such as Beton und Eisen (1901) and Proceedings of the American Concrete Institute (1905). The following sections describe bond-related papers published in each decade.

Figure 1 lists the number of papers surveyed. The papers are designated as "Author/Year/Journal Abbreviation/Volume/Pages"(ex. Graf/1940/DAfStb/94 /1-55,Giuriani/1991/ASCE /117 /1-18).

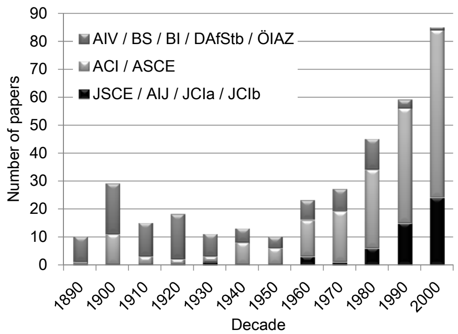


Figure 1. Number of surveyed papers.

2 BACKGROUND RESEARCH IN THE LATE 19TH CENTURY

Wayss & Freytag, an Austrian construction company with which M. Koenen was affiliated, pioneered in the development of RC techniques. The engineers of Wayss & Freytag made many contributions to Zeitschrift des Österreichischen Ingenieur- und Architekten-Vereins. Thullie, for example, refined the method of flexural analysis by introducing a bilinear stress-strain relationship of concrete under compression as well as a linear relationship under tension (Thullie/1897/ÖIAZ/18/193-197).

Iron reinforcement was gradually replaced with steel bars, not only in Austria and Prussia, but also in the USA. Wide-ranging discussions on construction, allowable stresses, elastic moduli of concrete, reinforcement ratios, reinforcement arrangements, temperature effects, and cast works were published in Transactions of the ASCE (Buck et al./1901/ASCE//93-128).

3 1900S

Wilhelm Ernst & Sohn, a publisher in Berlin, founded a journal on reinforced concrete, "Beton und Eisen." Beton und Eisen was later renamed Beton und Stahlbetonbau. It continues to publish today. In 1904, the Ministry of Public Works of the Prussian Government established the world's first RC design provisions (Ministerium für öffentliche Arbeiten 1904). This guideline specified allowable bond stress as being 4.5 kgf/cm^2 as well as tensile reinforcement stress at 1200kgf/cm^2, compressive concrete stress at 0.2 f'_c, shear stress at 4.5 kgf/cm^2, and the elastic modulus ratio of steel to concrete at 15.

The guideline was revised in 1907 and 1916 (Ministerium für öffentliche Arbeiten 1907, Ministerium für öffentliche Arbeiten 1920) and assimilated as part of the German Industrial Standards (DIN 0145) in 1925.

The first technical paper on bond testing was contributed by Carl von Bach in 1905 (Fig. 2; Bach 1905). The bond test used a concrete block measuring 220 mm^3 with steel bars of varied diameters (8 mm to 40 mm) and embedded lengths (100 mm and 300 mm), and estimated the relationships between bond force and slip displacement.

Koenen, Wuczkowski, and Löser considered bond splitting prevention along the longitudinal reinforcements in beams and estimated the required cover thickness and reinforcement spacing (Koenen/1905/BS/6/148-149, Wuczkowski/1908/BS /3/60-61, Löser/1908/BS/14/345-347). Doucas discussed the stress transfers between concrete and reinforcements based on an assumption of linear bond stress distribution (Doucas/1908/BS/9/215-222).

In 1907, Beton und Eisen introduced deformed reinforcements made in the USA (1907/BS/2/55, 1907/BS/3/84, 1907/BS/5/136). Patents for bond enhancement were submitted in Wien and Berlin in 1907. The former proposed rings arranged along the bar (Grimm/1907/ÖIAZ/20/380) while the latter proposed T-shaped reinforcement with a waved web (Franke/1907/ÖIAZ/20/380).

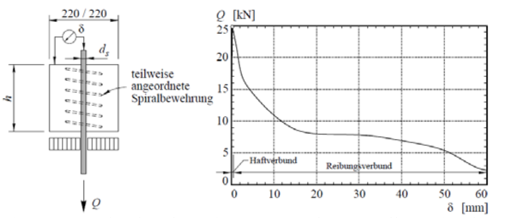
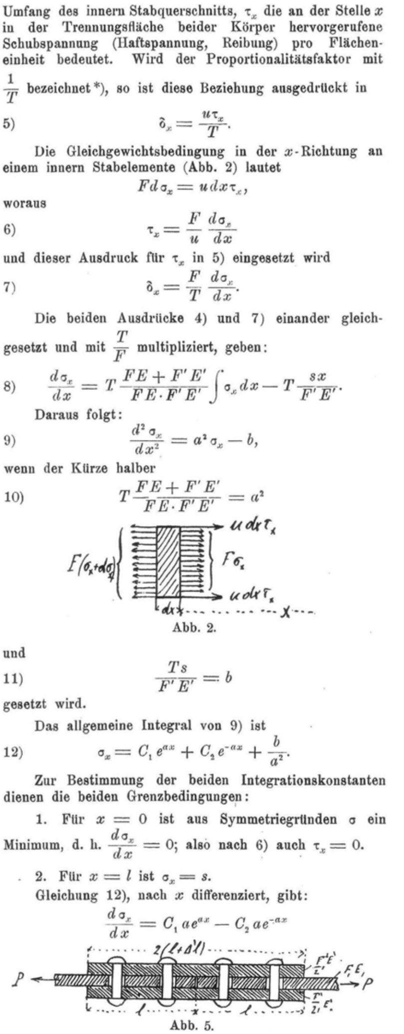


Figure 2. Bach's bond test in 1905 (Bach 1905; Illustration by Schenkel 1998).

It is thought that the first use of a differential equation for solving an interfacial bond problem in the civil engineering field, though not for RC, was Arnovljević's paper on the lap joint problem of iron plates in 1909 (Fig. 3; Arnovljević 1909). A second-order differential equation is derived based on an assumption of a continuous distribution of the interfacial shear force between welded or riveted iron plates. Equation 9 in Figure 3 expresses the differential equation with respect to the tensile stress of the iron plate σ_x. A linear relationship between the relative slip δ_x and the shear stress τ_x is assumed (Equation 5 in Fig. 3; u = width of plate, T = shear stiffness). The solution expressed by the hyperbolic functions (Equation 12 in Fig. 3) was derived, although no calculation example was presented.



Umfang des innern Stabquerschnitts, τ_x die an der Stelle x in der Trennungsfläche beider Körper hervorgerufene Schubspannung (Haftspannung, Reibung) pro Flächeneinheit bedeutet. Wird der Proportionalitätsfaktor mit $\frac{1}{T}$ bezeichnet *), so ist diese Beziehung ausgedrückt in

5) $$\delta_x = \frac{u\tau_x}{T}.$$

Die Gleichgewichtsbedingung in der x-Richtung an einem innern Stabelemente (Abb. 2) lautet

$$F d\sigma_x = u dx \tau_x,$$

woraus

6) $$\tau_x = \frac{F}{u}\frac{d\sigma_x}{dx}$$

und dieser Ausdruck für τ_x in 5) eingesetzt wird

7) $$\delta_x = \frac{F}{T}\frac{d\sigma_x}{dx}.$$

Die beiden Ausdrücke 4) und 7) einander gleichgesetzt und mit $\frac{T}{F}$ multipliziert, geben:

8) $$\frac{d\sigma_x}{dx} = T\frac{FE + F'E'}{FE \cdot F'E'}\int \sigma_x dx - T\frac{sx}{F'E'}.$$

Daraus folgt:

9) $$\frac{d^2\sigma_x}{dx^2} = a^2\sigma_x - b,$$

wenn der Kürze halber

10) $$T\frac{FE + F'E'}{FE \cdot F'E'} = a^2$$

Abb. 2.

und

11) $$\frac{Ts}{F'E'} = b$$

gesetzt wird.

Das allgemeine Integral von 9) ist

12) $$\sigma_x = C_1 e^{ax} + C_2 e^{-ax} + \frac{b}{a^2}.$$

Zur Bestimmung der beiden Integrationskonstanten dienen die beiden Grenzbedingungen:

1. Für $x = 0$ ist aus Symmetriegründen σ ein Minimum, d. h. $\frac{d\sigma_x}{dx} = 0$; also nach 6) auch $\tau_x = 0$.
2. Für $x = l$ ist $\sigma_x = s$.

Gleichung 12), nach x differenziert, gibt:

$$\frac{d\sigma_x}{dx} = C_1 a e^{ax} - C_2 a e^{-ax}$$

Abb. 5.

Figure 3. Derivation of second-order differential equation by Arnovljević (1909).

4 1910S

Carl von Bach and Otto Graf, principal professors at Stuttgart Institute of Technology, conducted tests on RC beams to estimate the effectiveness of anchors, lap splices, and diagonally bent longitudinal reinforcements. The test results were provided as seven large reports to the Deutscher Ausschuss für Eisenbeton during 1911 and 1917 (Bach/1911/DafStb/9/1-86, Bach/1911/DafStb/10/1-132, Bach/1911/DafStb/12/1-205, Bach/1912/DafStb/20/1-122, Bach/1913/DafStb/A/1-31, Bach/1913/DafStb/24/1-26, Bach/1917/DafStb/38/1-78). These works formed the basic method of measuring bond slip in RC members. In the US, the influence of bond slip on the reduction of flexural stiffness of beams was discussed by Scott (Scott/1911/ASCE/73/230-325). Duff Abrams conducted important bond research at the University of Illinois at Urbana during the 1900s and 1910s (Abrams 1913). The tests consisted of 1499 pull-out specimens (approximately 200 mm^3) and 110 beam specimens for bond creep observations (Fig. 5; 200 mm by 300 mm cross section). Influences of nine types of deformed reinforcements, concrete strength, curing condition, and loading condition were discussed. A number of empirical relationships between bond stress and slip and bond stress distributions along the beams were reported.

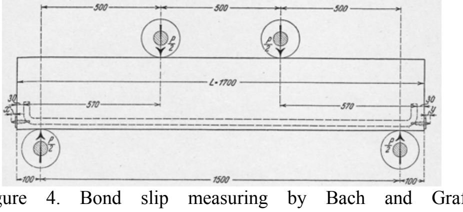


Figure 4. Bond slip measuring by Bach and Graf (Bach/1911/DAfStb/9/1-86).

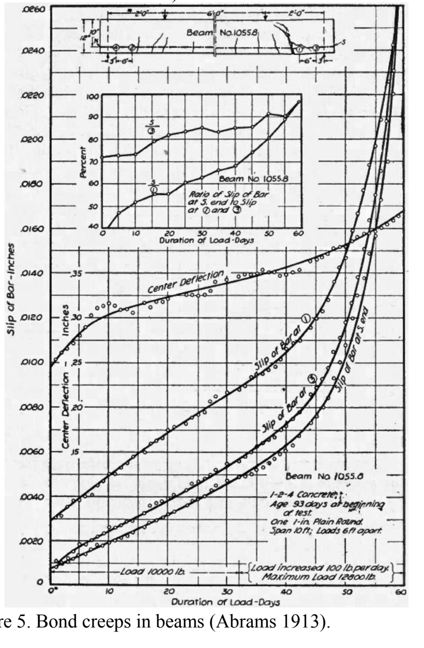


Figure 5. Bond creeps in beams (Abrams 1913).

A special committee on concrete and reinforced concrete established by six American associations including ASCE and ACI issued a final report in 1917 (ASCE/1917/81/1101-1206). This was the first American design guideline for RC. The report consisted of ten sections. Chapters 7 and 8 contained suggestions about bond strength and the spacing of reinforcements. For example,

1. A deformed bar is recommended when high bond strength is required although it should be noted that slip will occur at early loads.
2. Anchorage with 90° bends is less effective than with a 180° hook.
3. The lateral spacing of parallel bars should not be less than three diameters from center to center.
4. The cover thickness should not be less than two diameters.
5. The clear space between two layers of bars should not be less than 1 inch.
6. The bond strength of the round bar is assumed as 4% of the compressive concrete strength.
7. The bond strength of the drawn wire in the slab is assumed as 2% of the compressive concrete strength.
8. The bond strength of the deformed bar is assumed as 5% of the compressive concrete strength.

5 1920S -1930S

Emperger conducted pull-out tests with a variety of anchorage hook angles (Emperger/1935/BS/12/197-200) and different kinds of reinforcements including round bars and coupled twisting bars (Emperger/1938/BS/2/31-33). Abeles, a researcher in Wien, measured reinforcement strains and crack widths along four-point loaded beams with dial gauges (Fig. 6; Abeles/1937/BS/17/282-287). Gilkey, Iowa State University, conducted pull-out tests and flexural beam tests (Gilkey/1938/ACI//1-20) while Shank, Ohio State University, investigated bond creep (Shank/1938/ACI//81-90). Gilkey also employed many dial gauges to measure concrete strain.

At The University of Tokyo, Japan, Fukuda attempted to analyze bond stress distributions using a differential equation derived from the equilibrium and compatibility conditions of the bonding interface (Fig. 7; Fukuda/1933/JSCE/19_3/201-212). In the shrinkage example shown in Figure 7, it is suggested that the stresses of the reinforcement and the concrete would be underestimated by 45.4% if the bond action had been neglected.

6 1940S

Graf invented a cantilever specimen to simulate the anchorage behavior of diagonally bent, longitudinal reinforcements (Fig. 8; Graf/1940/DAfStb/94/1-55). The cantilever specimens were later used for not only anchorage tests but also for bond tests by RC researchers throughout the world. Emperger continued the precise measuring of bond behaviors through pull-out tests and four-point flexural beams (Emperger/1940/BS/7/91-99, Emperger/1940/BS/8/106-109). Since the 1930s, new kinds of deformed bars had been under development in America. Seven presentations on bond tests of new kinds of deformed bars were submitted to the ACI Journal (Watstein/1941/ACI//37-50, Watstein/1945/ACI//293-304, Kluge/1945/ACI//13-33, Clark/1946/ACI//281-400_9, Watstein/1947/ACI//1041-1052, Collier/1947/ACI//1125-1133, Clark/1949/ACI//161-184). All these studies were performed at the National Bureau of Standards (NBS). The tests used 17 kinds of bars (Fig. 9); influences of casting direction and air ratio were also discussed.

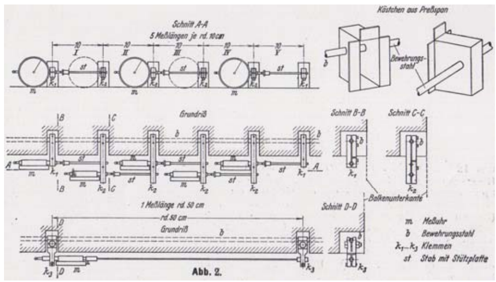


Figure 6. Strain measuring instrumentation of Abeles' test (Abeles/1937/BS/17/282-287).

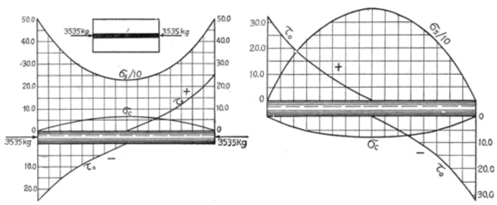


Figure 7. Example calculations by Fukuda (Fukuda 1933).

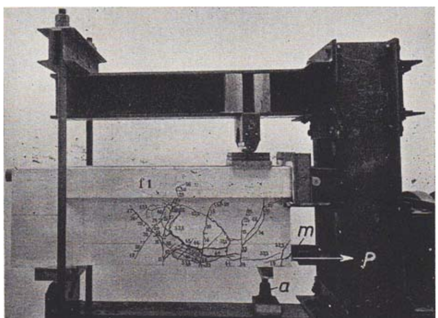


Figure 8. Cantilever specimen invented by Graf (Graf/1940/DAfStb/94/1-55).

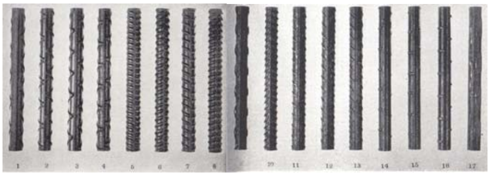
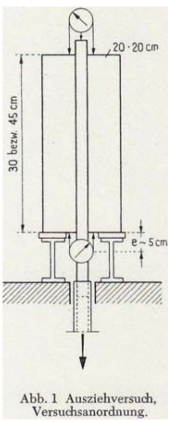


Figure 9. Deformed bars tested at the NBS during the 1940s (Clark/1949/ACI//161-184).

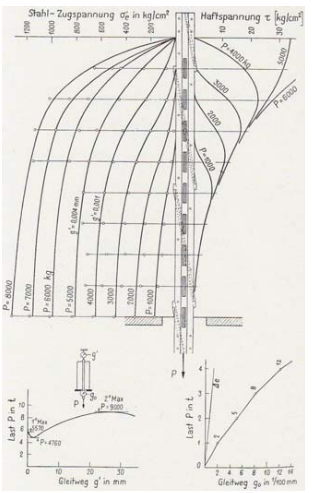
7 1950S

Hognestad, University of Illinois at Urbana, initiated the application of strain gauges for the strain measurement of steel reinforcements (Hognestad/1950/ACI//445-454). Hognestad also tested the influence of air ratio on bonds (Hognestad/1950ACI//649-667). Peatile, University of Nottingham, conducted torsion bond tests with concrete material of varied ages (Peatile/1956/ACI//661-672). Chi, NBS, observed the crack widths of beams reinforced with deformed bars (Chi/1958/ACI//865-878).

Bufler, a doctoral candidate at the Munich Institute of Technology, measured bond stress distributions along reinforcements made of glass fiber rods or duralumin embedded in an epoxy resin block (Bufler/1958/BI/33/382-388). Using a photoelastic device, Bufler computed bond stresses and slips by differential equations. Amstutz, at ETH Zurich, used strain gauges to measure bond stress distributions (Fig. 10; Amstutz/1955/BI/30/353-359). A minimum cover thickness regulation was added to the provisions of DIN 1045, which was revised in 1959.



(a) Specimen



(b) Distributions of steel stress and bond stress

Figure 10. Bond test using strain gauges at ETH (Amstutz/1955/BI/30/353-359).

8 1960S

In 1961, Rehm, Munich Institute of Technology, contributed an analytical study of bonds to Deutcher Ausschuss für Stahlbeton (Fig. 11; Rehm/1961/DAfStb/138/1-59). The analyses were conducted with various boundary conditions and visualized with precise figures. Rehm continued the bond research with Rüsch, preparing a number of four-point flexural beams reinforced with round and deformed bars up to 1964 (Rüsch/1963/DAfStb/140/1-182, Rüsch/1963/DAfStb/160/1-82, Rüsch/1964/DAfStb/165/1-52).

At around the same time, Leonhardt and Walther, Stuttgart Institute of Technology, began shear/flexural tests of beams reinforced with round and deformed bars. Leonhardt had contributed 13 papers to Beton und Stahlbeton during 1962 and 1965 (Fig. 12; Leonhardt/1962/BS/2/32-44, etc.).

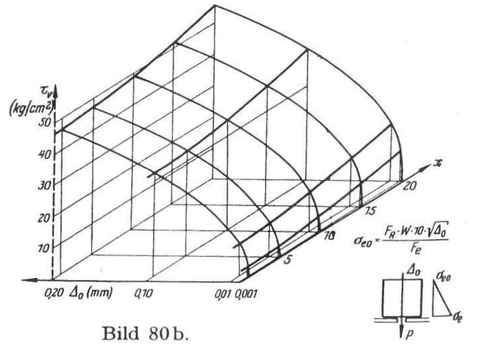
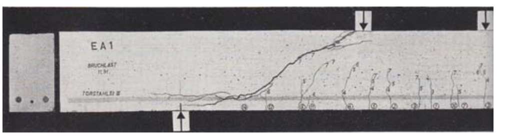


Bild 80 b.

Verteilung der Verbundspannung bei veränderlichem Δ_0.

Figure 11. Bond tests and analyses by Rehm (Rehm/1961/DAfStb/138/1-59).



(a) Beam with deformed bars

(b) Beam with round bars

Figure 12. Leonhardt's beam specimens (Leonhardt/1962/BS/2/32-44).

In America, in the early 1960s, the application of high strength steels to RC began. Bonds of 700 MPa-class (100 ksi-class) reinforcements were tested at NBS (Mathey/1961/ACI//1071-1090, Ferguson/1962/ACI//887-922, Ferguson/1965/ACI//933

-950). Ngo and Scordelis, University of California at Berkley, developed a finite element algorithm based on the discrete crack model and demonstrated the stress distributions of cracked beams (Ngo/1967/ACI//152-163). Ngo's research was the initial attempt to use a bond link element to model bond behavior along reinforcements.

Nilson, Cornel University, also simulated crack propagations based on the discrete crack model (Nilson/1968/ACI//757-766). In this analysis, bond stress distributions caused by new cracking were estimated. Bresler of UCB analyzed the repeated cyclic behaviors of uniaxial tension specimens (Bresler/1968/ASCE/ST5/1567-1590). Apart from the discrete crack approaches instituted by the above researchers, Rashid, Gulf General Atomic, developed the smeared crack model for RC structures (Rashid 1968).

The activities in Germany and America motivated Japanese bond research. Muguruma, Kyoto University, proposed a nonlinear bond stress-slip model and computed the bond behaviors of uniaxial tension specimens based on the differential equations of the bond problem (Muguruma/1967/AIJ/131/1-8, Muguruma/1967/AIJ/132/1-6, Muguruma/1967/AIJ/134/1-8).

9 1970S

Nilson cut a steel bar in half and made a groove along its length so that strain gauges could be embedded. This new instrumentation method successfully resulted in excellent observations of bond stress distributions (Nilson/1972/ACI//439-441). Martin attempted to visualize concrete stress distribution around a deformed bar by using a photoelasticity technique and proposed a ring tension model (Martin/1973/DAfStb/228/1-50). Tepfers, Chalmers University of Technology, also developed a ring tension model (Tepfers 1973).

In the 1970s, in America, the utilization of epoxy-coated steel bars began and many related studies of bonds were conducted. Mathey and Clifton, NBS, reported bond test results of epoxy-coated reinforcements in the ASCE Journal (Mathey/1976/ASCE/ST1/215-229, Clifton/1979/ASCE/ST10/1935-1947).

Dörr compared a number of bond stress-slip models that had been proposed in 16 reports and presented significant differences between them (Dörr/1974/DAfStb/238/29-102).

Losberg conducted bond splitting tests and presented classifications of bond splitting patterns (Losberg/1979/ACI//5-18). Eligehausen and Rehm, Stuttgart University (former Stuttgart institute of Technology), conducted finite element analyses of bond splitting behavior around lap splices (Fig. 13; Eligehausen/1979/DAfStb/300/13-38).

Goto, Tohoku University, Japan, attempted to visualize microcracks around reinforcements by injecting red ink into voids formed by cracks inside a concrete block (Fig. 14; Goto/1971/ACI//245-251). Morita, Kyoto University, developed a hysteresis model of bond stress-slip relationships based on cyclic push/pull tests (Morita/1975/AIJ/229/15-24).

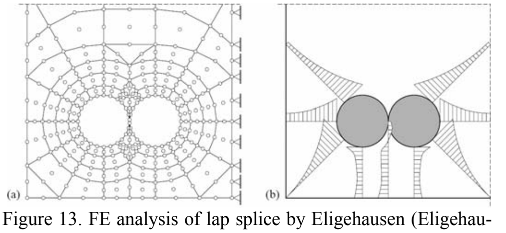


Figure 13. FE analysis of lap splice by Eligehausen (Eligehausen/1979/DAfStb/300/13-38; Illustration by Schenkel 1998).

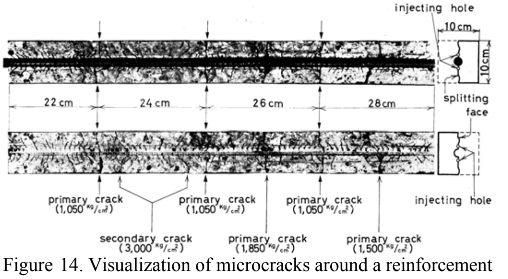


Figure 14. Visualization of microcracks around a reinforcement (Goto/1971/ACI//245-251).

10 1980S

Filippou and Popov, UCB, studied bond behaviors in beam-column joints during the 1980s (Filippou/1983/ASCE/109/2666-2684, Popov/1984/ACI//340-349, Fig. 15; Filippou/1986/ASCE/112/937-942, Filippou/1986/ASCE/112/1605-1622). The bond problem of the beam-column joint was one of the major concerns during the 1980s and many contributions were made by Harajli, American University of Beirut, (Harajli/1988/ASCE/114/2017-2035), Leon, University of Minnesota, (Leon/1989/ASCE/115/2261-2275), and Soroushian, Michigan State University, (Soroushian/1989/ACI//217-222).

Tepfers, Chalmers University of Technology, and Schober and Schmidt-Thrö, Munich Institute of Technology, continued the ring tension approach (Tepfers/1982ASCE/ST1/283-301, Schober 1984, Schmidt-Thrö/1988/DAfStb/389/175-197). Schober derived theoretical bond stress-slip relationships based on consideration of a local compressive deformation near the interface of the reinforcement.

Ingraffea, Cornell University, developed a finite element algorithm that rearranges the mesh division as the crack propagates (Ingraffea/1984/ASCE/110/871-890). Yankelevsky, Israel Institute of Technology, developed a two-node linear bond element so that the degrees of freedom are reduced in comparison to the conventional four-node bond link element (Yankelevsky /1985/ASCE/111/205-219). Keuser, Ingenieurbiiro Bung at Heidelberg, formulated several slip functions of the bond element and compared their accuracies (Keuser/1987/ASCE/113/2160-2173).

Shima, The University of Tokyo, proposed a bond stress-slip model as a function of reinforcement strain based on pull-out tests with massive concrete specimens (Shima/1987/JSCE/378/165-174, Shima/1987/JSCE/378/213-220).

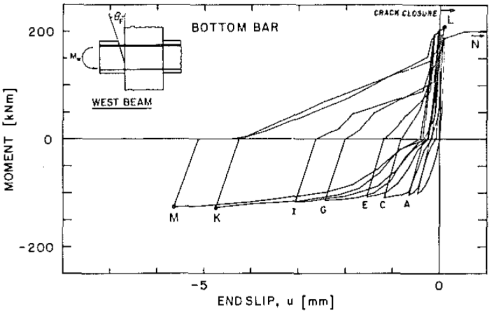


Figure 15. Computed slip along reinforcement in beam-column joint (Filippou/1986/ASCE/112/937-942).

11 1990S

Since the 1970s, through the ring tension approach, it was found that the surface geometry of deformed bars considerably affects bond behavior. Investigations of the influence of rib geometry on bonds were therefore accelerated in the 1990s. Darwin, University of Kansas, made cantilever specimens with various relative rib area ratios (Fig. 16; Darwin/1993/ACI//646-657). It was observed that bond strength and stiffness increased as the relative rib area ratio increased from 0.05 up to 0.20. Hamad, American University of Beirut, prepared bars with various rib angles (Hamad/1995/ACI//3-13). Bond stiffness increased as the rib angle increased from 30° to 60°, but did not increase when the angle was greater than 60°. Idun, University of Kansas, investigated the influence of the rib geometry of epoxy-coated bars (Idun/1999/ACI//609-615).

Many bond tests were performed for epoxy-coated reinforcements (Hadje-Ghaffari/1994/ACI//59-68, Cairns/1995/ACI//23-27, and Brearley/1990/ASCE/116/2236-2252) and for newly invented fiber-reinforced cementitious materials (Harajli/1994/ACI//511-520, Hota/1997/ACI//525-537, Naaman/1991/ASCE/117/2769-2790, and Naaman/1991/ASCE/117/2791-2800).

Giuriani of the University of Brescia proposed a semi-theoretical bond stress-slip model as a function of the splitting crack width (Fig. 17; Giuriani/1991/ASCE/117/1-18). Giuriani developed an equation that relates the confining reinforcement stress, the tension-softening stress of concrete, and the bond stress and numerically evaluated the bond slip. Kanakubo, Tsukuba University, Japan, also derived a theoretical bond stress-slip relationship under bond splitting failure (Kanakubo/1997/AIJ/492/99-106, Kanakubo/1998/AIJ/506/163-169, Kanakubo/1996/JCIa/18-2/527-532, Kanakubo/1997/JCIa/ 19-2/597-602).

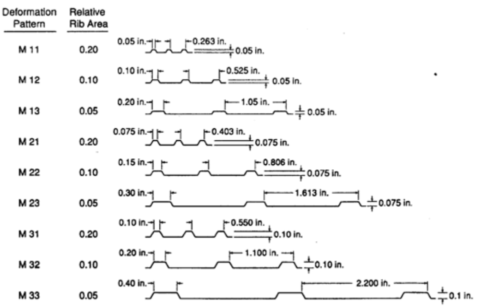


Figure 16. Bond test of deformed bars with various relative rib area ratios (Darwin/1993/ACI//646-657).

Yankelevsky, Israel Institute of Technology, proposed a hysteresis model of a bond stress-slip relationship allowing for deterioration due to cyclic loads (Yankelevsky/1992/ACI//692-698). Kankam, University of Science and Technology at Kumasi, Ghana, investigated the influence of reinforcement strain on the reduction of bond strength based on tests using specimens of grooved bars (Kankam/1997ASCE/123/79-85).

The amount of research on bonds between concrete and fiber-reinforced polymers (FRP) increased during the 1990s (Chajes/1996/ACI//209-217, Nanni/1992/ASCE/118/2837-2854, and Saiidi/1994/ASCE/120/2958-2976).

12 2000S

Bamonte, Politecnico di Milano, observed bond splitting crack widths in high strength concrete (Bamonte/2007/ASCE/133/225-234). Tammo, Lund University, measured the local deformation of concrete around a reinforcement (Tammo/2009/ACI//259-267). Chao, University of Texas at Arlington, conducted cyclic bond tests in high performance FRC (Chao/2009/ACI//897-906). Eligehausen, Stuttgart University, and Lowes, University of Washington, proposed bond stress-slip models as functions of many significant factors (Eligehausen/2000/DAfStb/503/1-89, and Lowes/2004/ACI//501-511). Studies of FRP bonds also continued through the 2000s (Nakaba /2001/ACI//359-367, Kanakubo/2001/JCIb/12_1/33-43, Kanakubo/2001/JCIb/12_3/27-37).

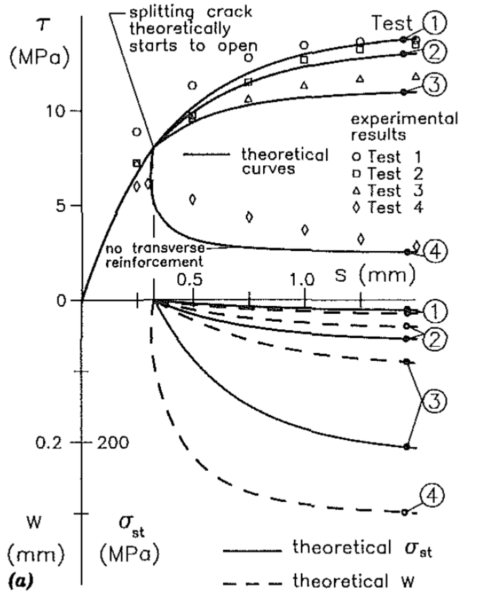


Figure 17. Relationships between bond stress, slip, and splitting crack width (Giuriani/1991/ASCE/117/1-18).

13 CONCLUDING REMARKS

The following remarks are based on our survey of 345 papers regarding bond problems, which were published in the United States of America, Germany, Austria, and Japan from the late 19th century to the early 21st century.

– Bond problems were recognized at the same time as the invention of reinforced concrete systems in the late 19th century. The world's first RC design provisions in 1904 describe an equation for the estimation of bond stress and the allowable bond strength of flexural beams.
– It is commonly thought that bond tests were also conducted in the late 19th century. Basic experimental methods including the pull-out test, the uniaxial tension test, and the method of measuring slip along the longitudinal reinforcement of a flexural beam were not developed until the 1910s.
– The cantilever-type bond testing method was invented by Otto Graf in 1940, although it was initially used as an anchorage test of longitudinal reinforcements.
– A considerable number of bond-related studies have occurred whenever new kinds of reinforcements were invented such as deformed bars, high strength bars, epoxy-coated bars, fiber-reinforced polymers, etc.
– The bond-related studies had dealt with flexural reinforcements and lapped splices in flexural beams by the 1960s. Studies of tension stiffening in RC plates began in the 1970s, and that of bonds of columns and beam-column joints began in the 1980s.
– The bond splitting problem has been recognized since the 1970s. The ring-tension model is proposed to investigate the mechanism of bond splitting.
– Second-order differential equations were first applied to bond problems in 1933. The pace of the analytical studies of bond problems began to accelerate after Gallus Rehm's research in 1961.
– Finite element analysis of RC structures was started by D. Ngo in 1967; the use of the bond link element was started in the same study.

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