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Historical Shear Experiments of RC Beams in Hungary and their Effect on Change of Shear Design

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Abstract

The shear behavior is one of the most mysterious physical phenomena of an RC (reinforced concrete) beam. Many shear-transfer actions (such as dowel action, cantilever action, aggregate interlock, tension softening, etc.) affect it. Still, there is no scientific agreement on the number and the role of these phenomena.

The paper investigates the historical development of these shear-transfer actions and the calculation models made from them through the glass of experimental research in the last one and half centuries in Hungary, in the context of the current international state of the art. This historical approach gives us an understanding of how the researchers and engineers of the past tried to understand the structure, and it leads us to accept that we are also on the way to understanding the shear behavior. However, the perfect model and understanding are far away from now. But are we on the right way?

Keywords

shear behavior, RC beams, history, behavior models, shear-transfer actions

1 Introduction

The investigation of the shear behavior of RC beams has a more than 100-year-old history. During this time, many experiments have been done, and numerous models have been developed, but the ultimate solution of calculating the shear resistance of a beam is still far away. It has at least three reasons:

1. According to the current state of the art, the shear resistance of a beam is a composition of lots of shear-transfer actions. These are competing and meaning different physical phenomena (e.g., cantilever action, aggregate interlock, dowel action, tension softening, arching action, etc.) [1].
2. The proportion of the influence of these actions is still under discussion [2, 3].
3. The engineering way of calculating the resistance of an RC beam has to be fast end simple [4].

It is easy to understand that finding a simple and exact solution to a complex problem is difficult. Nevertheless, many researchers and engineers were working on this slowly developing field as it is today.

In this paper, we would like to introduce the Hungarian aspects of this Sisyphus work as a part of international research through experimental tests conducted in Hungary.

2 Shear-transfer actions

As the first two reasons say, the 1D model of a reinforced concrete beam is not enough to determine how it works. The most recent models try to implement the shear-transfer actions into the 1D beam model. The shear-transfer actions are locally observed physical phenomena described by behavior models. These behavior models influence the resistance of a beam. Therefore, before the discussion of the historical steps of the field, these actions and their role – according to the authors' knowledge – should be explained.

One of the main shear-transfer action is the shear reinforcement: the *stirrups* and the *bent-up bars* (Fig. 1, σ_{str}). It was evaluated firstly by Mörsch [5]. The *dowel action* (Fig. 1, σ_{da}) is the longitudinal reinforcement's shear-carrying behavior based on its bending stiffness, described by Rasmussen [6], which works well with *stirrups.*

The shear-transfer action between the two rough crack surfaces is called *aggregate interlock* (Fig. 1, τ_{ai}), according to Walraven [7]. The combined behavior of *dowel action* and *aggregate interlock* is called *shear friction* (Mau and Hsu [8]).

The (*uncracked*) *compressed zone* (Fig. 1, τ_{uncr}) of the concrete also has a significant shear-carrying capacity [9].

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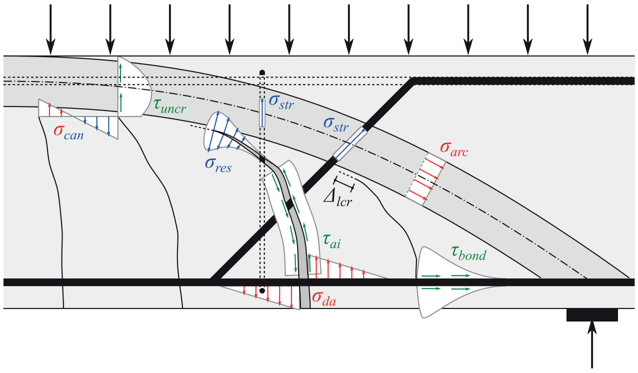

Fig. 1 Shear-transfer actions of a beam.
Tension – blue; compression – red; shear – green
Stirrups and bent up bars – σ_{str}, dowel action – σ_{da}, aggregate interlock and shear friction – τ_{ai}, uncracked concrete zone – τ_{uncr}, residual tensile strength - σ_{res}, cantilever action – σ_{can}, arching action – σ_{arc}, and bond between the reinforcement and the concrete or beam action – τ_{bond}, crack propagation – Δl_{cr}

In the vicinity of the crack tip, what is called FPZ (Fracture Process Zone), the concrete can still transfer normal stresses between the crack surfaces. According to the location and direction of the FPZ, the *residual tensile strength* (Fig. 1, σ_{res}) of the concrete affects the shear transfer between the two crack surfaces. The *crack propagation* (Fig. 1, Δl_{cr}) is the movement of the FPZ due to the increasing load [10].

The *cantilever action* (Fig. 1, σ_{can}) occurs when a concrete tooth – which is the concrete strip between two shear cracks from the longitudinal reinforcement till the compression zone – has to use its bending resistance to remain intact with the back of the "comb" – what is the compressed part of the reinforced concrete beam [11]. It is a simplified crack propagation model and a shear criterion too. Kani [11] thought that an RC beam could have three types of failure (Fig. 2): i) bending failure ("*Full flexural capacity*"); ii) strut failure ("*Capacity line of remaining arch*"); iii) concrete tooth failure ("*Capacity line of concrete teeth*"). The last one is based on the cantilever action.

In the case of high beams, the *arching action* (Fig. 1, σ_{arc}) can provide a significant portion of the shear resistance. It means that the mechanism of the beam is highly similar to the mechanism of a deep beam [12].

And the last known action is the *bond* between (Fig. 1, τ_{bond}) the reinforcement and the concrete [13]. It can also be called the *beam action* [12].

The previous shear-transfer actions are identified as separate physical phenomena and characterized by stress values, except for the *crack propagation* (Fig. 1, Δl_{cr}). This action is a movement, which can connect the separate shear-transfer actions because the stress is always a consequence of some movement, i.e., deformation. Therefore, it is essential to follow all the possible cracks on a beam because we cannot know at the beginning of a test where will be the critical crack that causes failure.

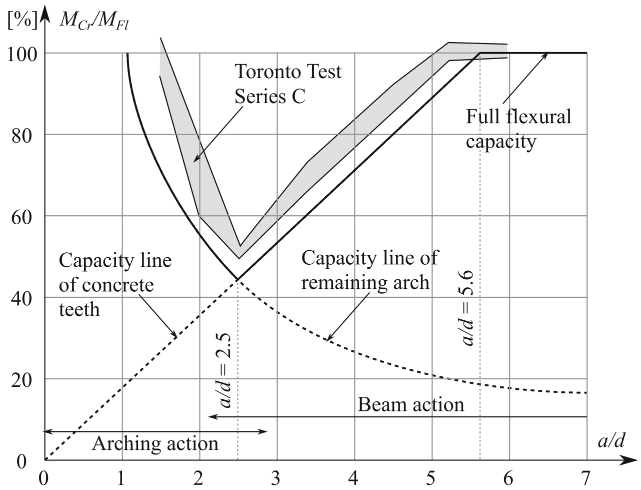

Fig. 2 Kani's valley according to [11]

Although the role of some actions is still under discussion, the authors try to set up order between them according to the provided load-bearing capacity part at the failure, in ascending order. According to Fernández Ruiz et al. [1], Classen [2], Autrup et al. [3], and Cavagnis [14], the recommended order is that if there is shear reinforcement in the beam:

1. *Stirrups and bent-up bars,*
2. *Dowel action,*
3. *Aggregate interlock and shear friction,*
4. *Uncracked compressed zone,*
5. *Residual tensile strength.*

According to Autrup et al. [3], Völgyi and Windisch [15], if there is no shear reinforcement, the *dowel action* and the *aggregate interlock* can be negligible. In that case, the recommended order is the following:

1. *Uncracked compressed zone,*
2. *Residual tensile strength.*

The previous shear-transfer actions (with or without shear reinforcement) are developing simultaneously in some interaction with each other. The sum of their resultant forces gives the shear resistance of the beam at the critical shear crack.

The role of the *arching*- and *beam* action depends on the shear slenderness (a/d – where d is the effective depth, a is the ratio of the maximum bending moment (M_{Cr}) and the maximum shear force (V_{CR})), as Kani [11] described it (Fig. 2), and on the bond behavior between the concrete and the reinforcement.

3 Shear tests in Hungary

3.1 The beginning of the RC application

The 19th century was the childhood of the RC.

The first non-building RC structure in Hungary was built in 1889. It was an RC bridge designed by Győző Zoltán [16].

The application of RC appeared later in residential and non-residential construction as well. The Franz Liszt Academy of Music was built between 1906 and 1907. All the slabs, floors, balconies, roof supports, and a few columns are RC. The designer of the structure was Szilárd Zielinszky and Zsigmond Jemnitz. [16]

The teaching of RC structure design started in the very early 20th century in Hungary. The first Faculty that educated this new and sometimes untrusted material was the Faculty of Architecture at the Royal Joseph University (today it is Budapest University of Technology and Economics) in 1905. The education was started at the Faculty of Civil Engineering two years later, in 1907.

Lampl and Sajó [17] researched the Hungarian journals of the 19th century but did not find any experimental papers. The test of reinforced concrete structures in Hungary was very rear in that era [18].

At that time, the RC structure was designed according to handbooks and personal experiences (spread by international companies and returned engineers from foreign working) because there was standardization neither in Hungary nor in any other European country. The first Reinforced Concrete Standard was published in 1903 in Switzerland, and the first Hungarian Standard was announced later, in 1909 [16, 19].

The basic principles of strength of materials were also applied to concrete. Nonetheless, in 1902, Mörsch [5] published his handbook for reinforced concrete design and construction, in which he presented a beam shear test. Since the evaluation of test results was not correct, the conclusions of the test have been corrected latter by Mohr [9].

3.2 Research in the first half of the 20th century

Before WWII, Hungarian researchers were part of the scientific life of the world. Some indicators show:

For example, one of the first RC standards in the world was the Hungarian one [16].

As conference proceedings testify [20–22], Hungarian professors and engineers were active participants in scientific life. They published a lot and discussed many publications as well. The best-known Hungarian researchers of the field in these times were: Adolf Czakó and Dr. Gábor Kazinczy (Fig. 3 [23]), Prof. Pál Csonka, Prof. Győző Haviár, Prof. Károly Széchy, Prof. László Palotás, etc.

Although most of the published papers were theoretical articles, there were also some about the shear experiments in the first half of the 20th century in Hungary.

3.2.1 RC beam test from 1903 by Ungár

Till the early 1900s, the most common tests were cube tests to describe the compressive strength of the cement paste (without aggregate).

As Ungár [18] described in the test report, the need to investigate the RC – not only the cement – has grown this time. The purpose of this need was to identify the resistance of the RC structures. This led to the experiment, which was taken by J. Jenő Kis, and József Schustler in 1903, and published in 1904 by Manó Ungár. Later Mihailich and Haviár [16] also cited this paper to highlight its importance.

The paper mentions 7 questions about the tested RC beams to answer. One of them was related to shear:

"*Do the stirrups have any role and importance in absorbing shear force?*"

In the early 1900s Ungar and his research partners did not have any RC standards, and they used only principles of experience and the rule of thumbs. This question had huge importance.

Fig. 3 Gábor Kazinczy, inventor of the plastic hinge and one of the most famous researchers of the theory of plasticity [23]

He tested thirtynine beams with different reinforcement types and w/c (water/cement) ratios. The tests were 3-point bending tests using a transformed hydraulic cube testing machine (further data in Table 1). The transformation had to be reversible to use the machine for cube testing after the experiment. The different stirrup variations did not affect the results. Still, the researchers did not take any long-term conclusions because they realized that the utilization of the stirrups was almost zero because of the small longitudinal reinforcement ratio. All the beams had a bending failure.

3.2.2 RC beam test from 1932 by Mihailich

In 1932, the new Hungarian Reinforced Concrete Regulation was published [24]. Mihailich has done experimental research to compare the results to the calculations of the Standard. [25]

The test setup was a 5-point bending test (1–1 support on both ends and 3 loading point in between the supports with equal spacing), and He tested 52 RC beams. The cross-section of the beams was "T" shaped (further data in Table 1 [15, 18, 24, 26–31]). However, the new Regulation did not consider the effect of composite action between the beam and the slab. He wanted to point out and prove based on the tests, that this instruction of the new Regulation is strict and uneconomical.

The tests have been made with two types of steel strength, four types of shear reinforcement methods, and five types of concrete strength.

Bending frames, hydraulic presses, and strain measurement devices were commonly used tools in Hungary at that time.

Most of the beams had a bending failure, but some failed because of the shear force. In some other cases, the anchorage of the longitudinal reinforcement failed. There was a beam series that had beams with bending- and beams with shear failure.

The three most important results were:

1. The failure of the longitudinal reinforcement anchorage significantly affects the shear resistance.
2. Increasing the compressive strength of the concrete does not increase the bond between the concrete and the reinforcement without limits.
3. In the case of a simply supported beam, the recommendation of the Standard gave 2- or 3-times higher reinforcement than necessary.

3.3 The COMECON era

After WWII, Hungary became part of the socialist block. The world became bipolar, making international scientific cooperation harder between the poles. In 1949 Hungary became a member of the COMECON (Council for Mutual Economic Assistance). The operation of this assistance influenced scientific work as well. The goal of that "Assistance" in the scientific field was the COMECON Standardization. That is why the final materials of these research were published in Russian, but the intermediate results were published only in the language of the researcher's country.

In the end, there were very few COMECON Standards in Hungary because of the Hungarian traditions of standardization. However, the scientific results were incorporated into the Hungarian Standards (MSz). The financial manager of the research topics in the building industry of

Table 1 The data of the mentioned beam tests in Hungary

Experiment	no. of spec.	X-point loading	b [mm]	h [mm]	d [mm]	l [mm]	a/d [mm]	ρ [%]	$f_{c,cube}$ [N/mm^2]	f_s [N/mm^2]	shear reinf.
Ungár - 1903 [18]	39	3	200	150	125	1100	4.40	0.64–1.54	21.1–45.6[1]	399	stirrups
Mihailich - 1932 [24]	52	5	500 (120)	400 (100)	N/A	3000	N/A	1.4	25.9–43.1	226–575	stirrups / inclined
Palotás and Juhász - 1965 [26–28]	76	4	100	200	N/A	1700–2100	2.72–3.84	1.26–1.76	19.5–24.8	318–380	yes / no
Palotás and Juhász - 1967 [29]	24	3	150	300	180 - 270	900	1.66–2.50	0.67–2.09	N/A	350	no
Vajk and Sajtos - 1990s [30]	18	3	100	141	126	1000	4.0	0.72 / 1.08	22.0–29.0[2]	500	stirrups
Draskóczy - 2009 [31]	24	∞[3]	500 (160)	500 (130)	N/A	4000	N/A	1.94 / 1.46+0.48[4]	37 (C30/37)	500 1770[4]	stirrups
Völgyi and Windisch - 2016 [15]	6 (12)[5]	3	120	220	185	1136	3.06–3.34	2.45–3.45	77.6 –84.6	500	stirrups

[1] 10 cm cube, [2] 15 cm cylinder, [3] uniformly distributed loading, [4] prestressing strand, [5] two tests on one specimen

Hungary was the ÉTI (Építéstudományi Intézet – Institute of Construction Science). Today's standardization groups are working according to numbered topics (MSz), the COMECON research projects also had their own numbering system. The topic number that covered all the RC research, including the shear, was 18, then 8.1 [32]. Unfortunately, it is very hard to get the more detailed topic content and numbering of this system.

It was common in this kind of research that the theory was supported by a large number of experiments as well. So financially, it was a very prosperous time for these experimental investigations.

As the bibliography of the following experiments testifies, access to international research papers was easier than before. The Hungarian researchers knew the most current international scientific results of the field, even if it was published in the Federal Republic of Germany, France, or the USA. It could be a journal article or Standard; it was available in Hungary. It was not rare that somebody was also a member of the Eastern and Western standardization groups [33].

3.3.1 Beam tests

The 1960s were the "Golden age" of shear tests with Leonhardt and Walther [34, 35] and Kani [11, 36], who made many beam tests. At that time, experiments with column-supported flat slabs became more common. The researchers started to make a difference in the shear behavior of beams and slabs. One of the most interesting research of this topic was done by Dalmy [37] about punching combined with bending of flat slabs.

RC beam tests from 1965 and 1967 by Palotás and Juhász

Palotás and Juhász made numerous RC beam tests at that time, knowing the work of Leonhardt and Walther very well. The experiments were published in different papers, and later Palotás published them in his RC theory book [26–29]. These tests had the following purposes:

1. Determining the role and the necessary amount of the shear reinforcement (stirrups and bent-up bars).
2. Investigate the effect of the angle of inclined stirrups.
3. Investigate the effect of longitudinal reinforcement on shear resistance.
4. Finding a reinforcement system that provides the same bending and shear resistance.

More than 100 beams were tested during the program, mostly with 4-point bending specimens (further data in Table 1).

An interesting part of the tests was that, in some cases, they did not use hydraulic jacks but a class two lever loaded with weights which occurred a 2.5 kN increment in each step (Fig. 4).

The most important results of Palotás and Juhász are:

1. The stirrups and the bent-up bars have the same effect. They are oversized according to the "conservative" model [38].
2. The inclined stirrups with a 45° angle is more effective than the vertical stirrups.
3. The longitudinal reinforcement has a significant effect on shear resistance. The effect depends on the stress in the bars, the bar diameter, and the thickness of the concrete cover.

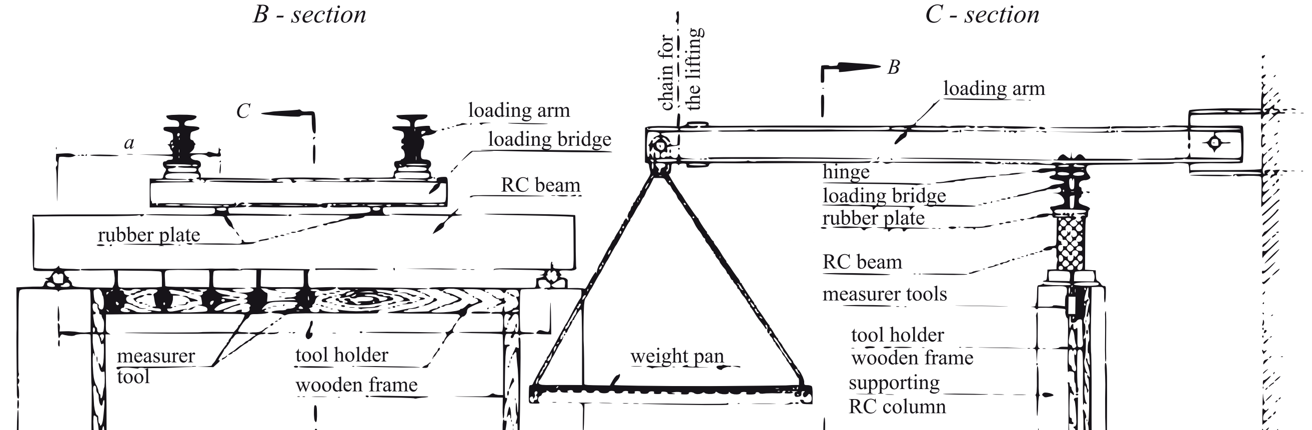

Fig. 4 Class two lever of the test of Palotás and Juhász (according to [26])

4. During the tests, one of the beam series resulted in different failures. Half of the beams had a bending failure, and the others had a shear failure.

Besides the original purposes, there are also some other interesting results:

- All the beams were symmetric, but the final crack formation was mostly asymmetric.
- The shear slenderness of Kani [11] has also been investigated with the same notation, and the results of the two groups were correlated very well [27]. However, the article of Kani did not appear between the references of the first papers, just between the references of the book [28] (6 years later).
- Palotás and Juhász applied the theory of Borisanskij (explained in: [39]), which says that before the failure, the beam can be investigated as two rigid bodies on the two sides of the critical crack. The connection between them is given by the compressed concrete, the shear reinforcement, and the longitudinal reinforcement.

This model is the former version of the most recent shear models in addition to the other shear-transfer actions described by Fernandéz Ruiz et al. [1] or Classen [2].

In 1966 Palotás presented these results at a conference held by the Építőipari és Közlekedési Műszaki Egyetem (Technical University of Building and Transportation, which is one of the predecessor institutions of Budapest University of Technology and Economics). At that conference, many researchers discussed the research. The discussion was published in the University's proceedings [40]. That shows this topic was very interesting and current, and the researchers and engineers were interested in it deeply.

Paper by Bölcskey and Kármán at 1970

In the late 1960s, it could be seen from the experiments of the "Golden age" that the more tests were made, the more tests had to be done to investigate all the peculiarity of the shear behavior.

Bölcskey and Kármán [41] formulated this problem in the following way:

"*The investigation of this question in an experimental way and the evaluation of these experiments involves a lot of difficulties because the shear resistance depends on a lot of things:*

- *the span size,*
- *the shear diagram,*
- *the grade of the concrete,*
- *the bent-ups of the reinforcement,*
- *the vertical stirrups,*
- *the inclined stirrups,*
- *the amount of the longitudinal reinforcement,*
- *etc.*

The separation of these effects in an experimental way, on the one hand, is difficult, and on the other hand, leads to a diverse series of experiments with extremely high costs and difficult evaluation." [41]

This led to the relapse of the shear experiments not just in Hungary but all over the world. This is the reason why before the publication of the new RC standard – called MSZ 15502/1 [42] – Bölcskey and Kárman did not do any experiments but evaluated 3 existing experiments from the literature.

The result of the evaluation was that the Standard keeps going with the international trends, because:

- It considers the shear resistance of the compressed zone [4],
- It keeps the shear safety level greater than the bending safety but not as high as the "conservative" model [26, 38],
- It accepts that the inclined stirrups give higher shear resistance than the vertical ones [26, 35].

3.3.2 Behavior model tests

In the 1960s, it turned out that the shear tests of RC beams were getting more and more complicated because of the different shear-transfer actions were distinguished.

Researchers started to make individual and unique specimens to investigate the behavior models separately.

RC slab tests between 1963 and 1964 by Lenkei

As was clarified before, the ÉTI (Építéstudományi Intézet – Institute of Construction Science) was the financial manager of the COMECON research projects. One of its research projects was taken between 1963 and 1964, led by Péter Lenkei [43].

During the research project, 45 circular slab specimen was cast with mesh reinforcement. The specimens had different reinforcement ratios in the two directions of the mesh. The circular shape specimens were used to investigate the effect of the reinforcement's directions between different cases. The specimens were tested with "4-point" loading (the loading was equally distributed by line supports). The loading was applied by a modified hydraulic jack setup. Tensometers, manual measurements, and electric strain gauges were used during the experiments to measure the crack widths, the elongation of the reinforcement, and the deflections of the slab.

The research aimed to investigate the yield condition of RC slabs, but dowel action appeared as a local effect during the experiments. The deformation ability of the investigated slabs depended on the dowel action, namely the length of the debonded reinforcement.

RC beam test from 1965 by Juhász

In the 1930s, Mörsch made a new and reworked edition of his famous book called "Die Eisenbetonbau" [5]. In the book, he described how to calculate the shear reinforcement through a crack. He also made a design guide with many tables using this new method [38]. This method is called the "conservative" model by Juhász.

In 1965 he made a test [4] series of 21 concrete beams to point out one of the weaknesses of Mörsch's method. The experiment was about the effect of compression on the shear resistance of concrete. This effect was neglected by Mörsch. Juhász tried to approach Mohr's theorem about the shear stress increment due to the compression [9] in a more simplified way to make a usable method for everyday engineering practice.

Based on the tests – where the cross-sections subjected to shear had different compression zone heights in each test – he suggested a linear correlation between the relative compression stress and the relative shear stress (Fig. 5). This relationship allowed him to apply shear stress to the compressed zone of a cross-section subjected to bending and shear. In this way, he showed that the compressed zone could have a huge influence on the shear resistance.

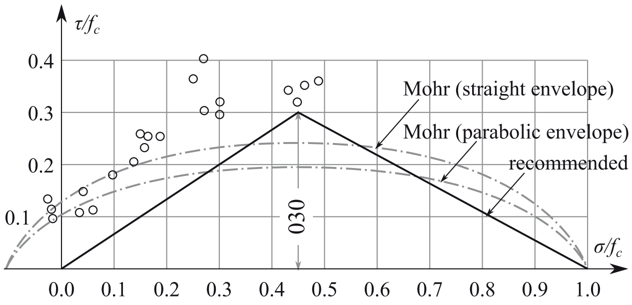

Fig. 5 The experimental results (○), Mohr's theorem (the envelops of the Mohr-circles – parabolic or straight) and the recommended linear connection between the compression and shear stress (according to [4])

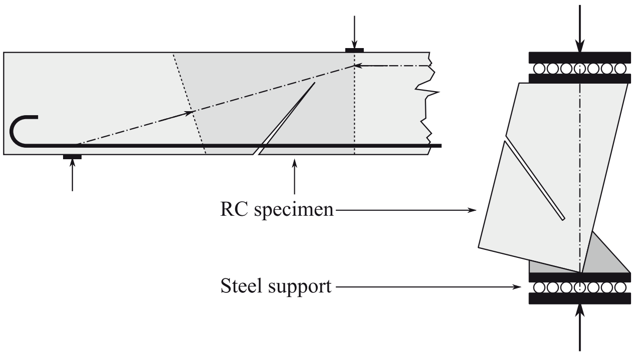

Fig. 6 Imaginary beam (left) and experimental setup (right) of Kármán's test (according to [32])

RC specimen tests from 1965 and 68 by Kármán (ÉTI)

Another important ÉTI project was the research of Tamás Kármán [44] between 1965 and 1968.

Kármán mentioned in the report's introduction that the truss model of Mörsch [5] neglects the effect of the propagation of the cracks. He mentioned Borisanskij (explained in: [39]), who made a limit equilibrium method for the oblique section. He considers crack propagation, but the method is not suitable for everyday engineering practice.

During the research project, 91 special specimens were cast and tested to find out the shear resistance of the compressed zone of a reinforced concrete beam (Fig. 6). A hydraulic jack was applied to the loading, and the deformations of the specimens were measured with strain gauges.

The goal of the research was to define the parameters that influence the shear resistance of the compressed concrete zone and what is the role of this zone of the RC beams. The results were compared to existing international RC beam tests without shear reinforcement.

As a result, Kármán suggested an equation to calculate the shear resistance of the compressed zone of the beam. It considers the height of the compressed zone, the arching action (the direction of the crack), and the strength of the concrete.

RC specimen tests from 1970 by H. Dulácska

Ilona Dulácska Endréné Szederjei (H. Dulacska) presented her experiments and research on dowel action in the ACI Structural Journal [45]. The article's length was very limited, but a detailed description of the experiments was published in her doctoral thesis [46]. The recent theories and experiments about dowel action [43, 47] use and reference her experiments and results.

During the research project, 16 special specimens were cast and tested to examine the dowel action phenomenon.

The 3 most important findings of the experiments were:

1. "*The behavior of the dowel action is almost ideally elastoplastic.*
2. *The interaction between the shear and tension forces in the bar can be represented by an ellipse*." [45]
3. She created a formula to define the dowel action resistance.

3.4 After the end of socialism in Hungary

After the socialist era, the COMECON was dissolved as well as the ÉTI. The financial management of science returned to the hand of the universities, the Hungarian Academy of Sciences, and the government. There was no longer foreign control over it.

The experimental research of the shear behavior was slowly returned to the Hungarian laboratories. For example, the work of Völgyi and Windisch [48, 49] on hollow circular cross-section beams.

3.4.1 RC beam test from the 1990s by Sajtos

Vajk and Sajtos [30] published a paper in 2015 that presented an unpublished experiment from the 1990s.

The experiment's goal was to show that the strength of the concrete and the reinforcement and the geometry of the beam (the usual parameters) is not enough to estimate precisely the load-bearing capacity and the deformation ability of an RC beam.

The test setup was 3-point bending, using 18 specimens (further data in Table 1). A hydraulic jack was applied for loading. The deformations of the specimens were measured with strain gauges and inductive sensors.

Three different aggregate compositions and two different reinforcement ratios were used. According to the Model Code 1990 [50], Sajtos knew that the different aggregate sizes result in different fracture energy for the same concrete grade.

Vajk and Sajtos presented a model that uses the usual parameters and fracture energy. The shear resistance calculation model and the experiment results show that the aggregate size has some effect on the shear resistance, the failure mode, and the deformation ability of the RC beam without shear reinforcement. Later Ther and Sajtos [51] examined numerically the same phenomenon.

3.4.2 RC beam test from 2009 by Draskóczy

Draskóczy [31] published extensive experimental research in 2009, which considers the critics of Kollár and Dulácska's [52] on Draskóczy's former work [53].

The dispute was about the arching action in the case of uniformly distributed load and the angle of the strut inclination. Draskóczy made a more detailed calculation method to evaluate the beams' shear resistance, considering the arching action based on experimental results.

Different stirrup spacing was used in the experiment to affect the strut inclination angle, executed with 24 beams (further data in Table 1). The loading was uniformly distributed with the help of a PVC sack filled with water.

During the test, many strain gauges, tensometers, and manual measurements were used to measure the propagation and width of the cracks and the deflection of the beam.

The experiment's finding was a better estimation of the strut inclination angle than what Eurocode 2 gives [54].

3.4.3 RC beam test from 2016 by Völgyi and Windisch

In 2016 Völgyi and Windisch [15] conducted their research in accordance the international trends. They knew the work of Collins [55], Tasevski et al. [56], Sneed and Ramírez [57], and Wight et al. [58] etc., about the recent shear theories and shear transfer actions.

The main question of the research was how the aggregate interlock influences the resistance and the behavior of RC beams. In other words, what is the role of the aggregate interlock under "*combined shear-bending*".

They investigated 12 beams of cantilevered, 3-point bending specimens loaded by a hydraulic jack during the test (further data in Table 1). For the measurement, photogrammetry and manual methods were used.

An exciting part of the experiment was that the aggregate interlock was excluded in some specimens with a diagonally inserted plastic sheet. This method made an artificial crack between the tensioned and compressed reinforcement. With the help of this method, they could compare beams with and without aggregate interlock.

The most interesting finding of the research was that "*[...] aggregate interlock in the tensile zone is practically negligible under combined shear-bending of RC beams. However, the contribution of aggregate interlock in the compression zone to the shear resistance is relevant*." [15]

4 Conclusions

It can be seen that experimental research was important and advanced in the past in Hungary.

The recent RC modeling theories [1, 2] are part of the development of the scientific field. According to this development, shear-transfer actions provide the shear resistance

Table 2 The "first" appearance of shear-transfer actions and their corresponding experiments in Hungary

Shear-transfer actions	First appearance in literature [59]	Hungarian experiments
stirrups and bent up bars	Mörsch, 1902 [5]	Ungár, 1904 [18], Palotás and Juhász, 1965, 1967 [26, 29], Palotás, 1967, 1973 [27, 28]
dowel action	Rasmussen, 1962 [6]	Lenkei, 1966 [43], Palotás and Juhász, 1967 [29], Palotás, 1967, 1973 [27], Dulacska, 1972 [45]
aggregate interlock	Walraven, 1981 [7]	Völgyi and Windisch, 2017 [15]
uncracked concrete zone	Mohr, 1911 [9]	Juhász, 1965 [4], Kármán, 1968 [44]
residual tensile strength (fracture energy)	Hillerborg et al., 1976 [10]	Vajk and Sajtos, (1990s) 2015 [30]
cantilever action	Kani, 1964 [11]	-
arching action	Park and Paulay, 1975 [12]	Draskóczy, 2009 [31, 53]
bond or beam action	Rehm, 1957 [13], Park and Paulay, 1975 [12]	Mihailich, 1934 [24], Palotás and Juhász, 1965 [26]
crack propagation	Hillerborg et al., 1976 [10]	-

in the RC beams. The Hungarian engineers and researchers aided this development. These contributions can be seen in Table 2. The shear-transfer actions are in the left column. The first appearance of the shear-transfer action theory in the literature is in the second column. The Hungarian experiments are listed by time and authors in the third column.

It can be seen that the experiments which have been taken in the last more than 100 years are organically connected to the recent state of the art. It is common in them that crack propagation is not investigated directly. The two sides of the critical crack are modelled as two rigid bodies, but nobody investigated the location and the propagation of the critical crack. It means that with the help of the mentioned scientific results, the failure cannot be modelled and followed from the initial state. These are methods and evaluations of the final state according to the theory of plasticity. But the way between the initial and final state is not part of the scientific conversation.

It is also important that the calculation models developed are based on steel structure calculations, which is why the effect of shear and bending were investigated separately. But in the case of RC structures, this approach is giving us a false sense of safety.

It can also be seen that the investigation of shear behavior is far from its end, and further research has to be done, to make a precise but simple model for everyday use. Maybe the right way now is to take one step back and try something new instead of combining the beam model and the shear-transfer actions.

A complex model should include cracks, and all the behavior models of the shear-transfer actions, i.e., physical effects, that influence the shear resistance of the RC beams.

A possible solution could be to consider the curved (shear) crack and its propagation in the model. The crack opening is essential and easy to measure displacement in experiments. The crack propagates in the Mode I., opening, state (according to principles of fracture mechanics) at the crack tip, i.e., only crack opening develops there. However, due to the displacement kinematics of the curved crack, the opening at the crack tip also generates crack-sliding along the curved crack.

The crack opening at the crack tip makes to develop residual tensile stress in the fracture process zone, and influence and define the normal and shear stress in the compressed part, in the vicinity of the crack tip. The crack opening and sliding along the shear crack makes to develop: i) tensile stress in shear reinforcement (if there is one), ii) transversal forces (i.e., dowel action forces) in longitudinal steel bars, iii) aggregate interlock and shear friction forces, iv) tensile stress in longitudinal steel bars. All these shear-transfer actions interact and compete during the loading process corresponding to the change of crack geometry, opening, and sliding. The possibility of (stable or unstable) crack propagation is also influenced by how the shear reinforcement, axial and dowel stiffness of the longitudinal steel bars, and aggregate interlock characteristics of concrete limit or reduce the crack opening and sliding.

That is, the shear-transfer actions and their behavior models are not independent of each other, and their effect on beam shear resistance depends on the interaction between them.

This way of understanding has its root in past experimental experiences and hopefully does not contradict any explanation based on those either.

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