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# Shear tests of beams reinforced longitudinally and transversely with FRP bars

## *Badania na ścinanie belek zbrojonych podłużnie i poprzecznie prętami FRP*

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**Abstract.** This article presents a review of research in the field of shear tests of beams with longitudinal and transverse FRP reinforcement. The research review includes a summary of the parameters of various variables: type of reinforcement, depth of the element, width of the beams, shear span to depth ratio, compressive strength of concrete, longitudinal and transverse reinforcement ratio, modulus of elasticity of bars, shape of stirrups, comparison with elements reinforced with steel bars, as well as the static scheme. Based on the foreign studies the own research program has been proposed.

**Keywords:** shear; FRP; GFRP stirrups; T-section beams; Shear strength.

**Streszczenie.** W artykule przedstawiono przegląd literatury w dziedzinie badania na ścinanie belek zbrojonych podłużnie i poprzecznie prętami FRP. Przegląd badań obejmuje zestawienie parametrów różnych zmiennych: rodzaju zastosowanego zbrojenia; wysokości użytecznej elementu; szerokości belek; smukłości ścinania; wytrzymałości betonu na ściskanie; stopnia zbrojenia podłużnego i poprzecznego; modułu sprężystości prętów; kształtu strzemion; porównania z elementami zbrojonymi prętami stalowymi, a także schematu statycznego. Na podstawie przeglądu wiedzy zaproponowano program badań własnych.

**Słowa kluczowe:** ścinanie; FRP; strzemiona GFRP; przekrój teowy; nośność na ścinanie.

The issue of shear in reinforced concrete structures is very complex due to the simultaneous action of moment and transverse force in the support zones [1, 2]. The complex state of stress caused by the simultaneous occurrence of bending moment and transverse forces, is difficult to describe unambiguously, especially since the concrete and transverse reinforcement cooperate in the transfer of shear force in the first place, and also indirectly the longitudinal reinforcement designed for bending. Thus, shear in concrete beams depends not only on the tensile and compressive strength of the concrete, but also on the properties of the longitudinal reinforcement and transverse reinforcement [1, 3, 4].

The shear phenomenon in the support zone is a multifaceted issue due to the presence of several mechanisms of transverse force transmission, inside the concrete element under load. The primary mechanisms include the contributions of force through transverse reinforcement $V_s$, force in the compressed zone of uncracked concrete $V_c$; friction along the crack due to aggregate interlock $V_a$, dowel action $V_d$ and residual tensile strength of concrete across the diagonal crack [2, 4]. These contributions are shown in Figure 1.

The shear capacity is affected by many factors, including the shape of the section of the element, the type, amount and spacing of longitudinal and transverse reinforcement, the strength of the concrete and bars, the modulus of elasticity of the reinforcement, the bond behaviour of the composite bars to the concrete, the type and size of the aggregate, and the effect of shear slenderness [1 – 4].

Composite bars made of FRP *(Fiber Reinforced Polymer)* fibers are increasingly used as a replacement for traditional steel reinforcement, especially in concrete structures. The main reasons for using non-metallic reinforcement in concrete include: lack of magnetic properties, high tensile strength, very low weight (composite bars are 3.5 to 6 times lighter compared to steel, which significantly reduces the cost of transportation and installation of such reinforcement). Undoubtedly, one of the biggest advantages of FRP materials is the high ratio of tensile strength to material weight, which is about 10 – 15 times higher than for steel. In addition, composite reinforcement provides high durability of reinforced concrete due to good chemical resistance and corrosion resistance [5]. The mechanical properties of FRP composite reinforcement differ in many respects from conventional steel reinforcement, and largely depend on the type of fibers and resins used in the production of the reinforcement [6]. The anisotropic structure of

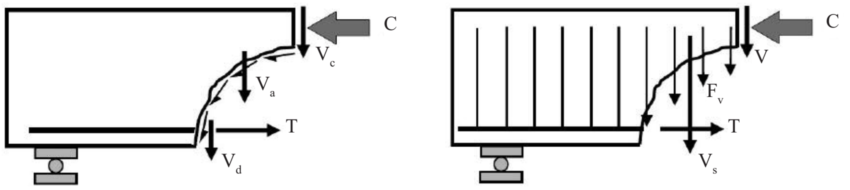

**Fig. 1. Contribution of concrete and reinforcement to load transfer**
*Rys. 1. Udział betonu i zbrojenia w przenoszeniu obciążeń*

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composite bars causes them to exhibit completely different mechanical properties in both directions.

The shear capacity of beams is more complex when the longitudinal and transverse reinforcement is made of anisotropic composite bars. In addition, FRP reinforcement, due to its linear-elastic characteristics, cooperates quite differently in transferring shear stresses, compared to steel reinforcement.

Despite the developed theoretical basis of the issue of design of shear zones, the emergence of new theories and models of shear and modification of existing ones, the development of original formulas on the basis of own experimental studies, the problem of shear is still current and topical. Although guidelines and standard procedures for the design of elements reinforced with composite bars have already been developed (American ACI 440.1R-15, Italian CNR-DT-203/2006, Canadian CAN/CSA S806-12, Japanese JSCE and other foreign standards), Polish recommendations have not yet been developed, so designers use foreign design procedures

## Characteristics of the literature database

Based on the analysis of selected literature, a database was created, including shear tests of concrete beams reinforced longitudinally in bending and transversely in shear with composite bars [3, 4, 7 – 39]. Only elements with transverse shear reinforcement were analyzed.

A number of studies were analyzed, from which the following variable parameters analyzed in the research programs were extracted: depth *d*, beam width *b*, shear slenderness *a/d*, concrete compressive strength $f_c$, longitudinal reinforcement ratio $\rho_l$, transverse reinforcement ratio $\rho_t$, longitudinal modulus of elasticity of reinforcement *E* and shape and type of transverse reinforcement *(O/U)*. The symbol *S* denotes research programs containing elements reinforced only with steel bars with the same variable parameters as beams reinforced with composite bars. Table 1 lists the 35 experimental papers selected and analyzed, detailing the variable

**Table 1. Variable parameters in research programs**

*Tabela 1. Parametry zmienne w programach badawczych*

| Autorzy | FRP | d | b | a/d | $f_{ck}$ | $\rho_l$ | $\rho_t$ | E | O/U | S |
|---|---|---|---|---|---|---|---|---|---|---|
| Nagasaka, Fukuyama, Tanigaki, 1993 | C, A, G, H | | | ● | ● | | ● | | | ● |
| Tottori i Wakui, 1993 | C, G, A | | | | | ● | ● | ● | | |
| Maruyama i Zhao, 1994 | C | | | | | ● | ● | | | |
| Okamoto, Nagasaka, Tanigaki, 1994 | A, C | | | ● | | | ● | | | |
| Zhao, Maruyama, Suzuki, 1995 | G, C | | | ● | | ● | | ● | | |
| Nakamura i Higai, 1995 | G | | | | | | ● | | | |
| Vijay, Kumar, Ganga Rao, 1996 | G | | | | | ● | ● | | | |
| Zhao, Maruyama, 1996 | C, G | | ● | | | | ● | | | |
| Duranović, Pilakoutas, Waldron, 1997 | G | | | ● | | | ● | | | |
| Alsayed, Al-Salloum, Almusallam, 1997 | G | | | | | ● | ● | | | ● |
| Shehata, Morphy, Rizkalla, 2000 | G, C | | | | | | ● | | | |
| Alkhrdaji, Wideman, Belarbi, Nanni, 2001 | G | | | | | ● | ● | | | |
| Guadagnini, 2002 | G, C | | | ● | | | ● | | | |
| Whitehead, Ibell, 2005 | A | | | | | ● | ● | | ●[1] | |
| Guadagnini, Pilakoutas, Waldron, 2006 | G, C | | | ● | | ● | ●[2] | ● | | |
| Matta, Nanni, Galati, Mosele, 2007 | G | | ● | | | ● | ● | | | |
| Imjai, 2007 | G, C | | | | | ● | ● | | | |
| Hegger, Niewels, Kurth, 2009 | G | | | | | ● | ● | | | |
| Niewels, 2008 | G | | | ● | | ● | ● | | | |
| Ascione, Mancusi, Spadea, 2010 | G, C | | | | ● | ● | | | | |
| Spadea, 2010 | G, C | | | | | ● | | ● | | |
| Ahmed, El-Salakawy, Benmokrane, 2010 | C | | | | | | ● | | | |
| Bentz, Massam i Collins, 2010 | G | ● | | | | | ● | | | |
| El-Mogy, El-Ragaby, El-Salakawy, 2011 | G | | | | | | ● | | | |
| Kamińska, Szymczak, Olbryk, Chołostiakow, 2012 | G | | | | | | ● | | | |
| Yang, 2014 | G, C | | | ● | | | ● | ● | | |
| Tomlinson, Fam, 2014 | B | | | | | ● | | | | |
| Issa, Ovitigala, Ibrahim, 2015 | B | | | ● | | ● | | | | |
| Said, Adam, Mahmoud, Shanour, 2016 | G | | | | ● | | ● | | | |
| Bywalski, Drzazga, Kaźmierowski, Kamiński, 2016 | G | | | | | | ● | | ●[3] | |
| Chołostiakow, Di Benedetti, Pilakoutas, Guadagnini, 2018 | C, G, B | ● | | | ● | | | | | |
| Jumaa i Yousif, 2019 | B | ● | | | | | ● | | | |
| Krall i Polak, 2019 | G | | ● | | | ●[4] | ● | | ●[5] | |
| Yuan i Wang, 2019 | C | | | | | | ●[6] | | | |
| Fan, Zhou, Tu i Zhang, 2021 | B | ● | | | | | ● | | | |
| Szczech, Kotynia 2022 | G | | | | | ● | ● | | | ● |

● research program analyzed the effect of a given variable parameter on shear capacity. Symbol designation: FRP – type of bars used (G-glass, C-carbon, A-aramid, B-basalt, H-hybrid), d – depth of element, a/d – shear slenderness, $f_c$ – concrete strength, $\rho_l$ – longitudinal reinforcement ratio, $\rho_t$ – transverse reinforcement ratio, E – modulus of elasticity of bars, O/U – the influence of the shape of the transverse reinforcement; [1] – the effect of the shape of the transverse reinforcement (continuous spirals and rectangular helixes) and the location of this reinforcement; [2] – used transverse reinforcement in the form of external stirrups; [3] – the influence of the type of transverse reinforcement: closed stirrups and vertical bars with head anchorage; [4] – the influence of the number of layers of longitudinal reinforcement, diameter and arrangement of bars in the section; [5] –the influence of the diameter of the transverse reinforcement and its spacing; [6] – effect of slope and spacing of stirrups factors studied. In the last column of the table, research programs containing more than one beam element with steel reinforcement are marked in order to relate the results of beams reinforced with composites to those reinforced with traditional steel reinforcement.

Due to the variety of variable parameters in the research, a simplified form of the database is presented as an abbreviated list of variable parameters analyzed in the foreign research programs (Table 1). In the analysis of variable parameters, the analysis was limited only to test elements transversely reinforced in shear with composite bars.

## Analysis of foreign research

The analysis of previous research has made it possible to identify 35 research papers on the basis of which 191 single-span, simply supported beams, reinforced longitudinally and transversely with composite bars, were analyzed. The extreme values of the variable parameters, along with the mean value and standard deviation, are shown in Table 2.

Beams with a rectangular cross-section made up the majority of the elements. Only 6 beams had a T-section (Figure 2). This fact prompted the authors to conduct their own tests on more demanding beams with a T-section, taking into account the interaction of the flanges with the web.

Nearly 1/3 of the test elements included a three-point scheme, where the load was applied through 1 hydraulic jack (Figure 2). In contrast, 2/3 of the beams were loaded with 2 concentrated forces (four-point static scheme). In four beams, the elements were tested twice, first in The research programs reviewed adopted four types of longitudinal reinforcement: glass GFRP bars (43%), carbon CFRP bars (27%), aramid AFRP bars (23%) and basalt BFRP bars (6%). The vast majority of the research programs assumed a uniform type of longitudinal and transverse reinforcement. A few programs used a mixed type of reinforcement (different type of longitudinal bars and different type of stirrups), as reflected in the graph in Figure 3.

**Table 2. Variable parameters of research elements in the database**
*Tabela 2. Parametry zmienne badanych elementów z bazy danych*

| Parameter | Minimum value | Maximum value | Average value | Median | Dominant | Standard deviation |
|---|---|---|---|---|---|---|
| **Geometry** | | | | | | |
| h [mm] | 200 | 1000 | 360 | 300 | 300 | 152 |
| b [mm] | 110 | 914 | 207 | 200 | 150 | 97 |
| d [mm] | 145 | 937 | 304 | 253 | 250 | 135 |
| **Static scheme** | | | | | | |
| $L_{tot}$ [mm] | 1500 | 7000 | 2901 | 3000 | 3300 | 798 |
| $L_{span}$ [mm] | 600 | 5000 | 1986 | 2000 | 900 | 943 |
| a [mm] | 300 | 3050 | 821 | 700 | 625 | 466 |
| a/d [-] | 1,2 | 4,4 | 3,0 | 2,6 | 2,5 | 1,0 |
| **Concrete** | | | | | | |
| $f_c$ [MPa] | 20,0 | 84,2 | 42,0 | 37,7 | 48,0 | 15,0 |
| $a_g$ [mm] | 8 | 20 | 11 | 10 | 9,5 | 4 |
| **Longitudinal reinforcement** | | | | | | |
| $\rho_l$ [%] | 0,32 | 3,98 | 2,00 | 1,43 | 1,90 | 1,00 |
| $E_l$ [GPa] | 29 | 165 | 72 | 58 | 56 | 33 |
| $f_l$ [MPa] | 397 | 2200 | 1058 | 1089 | 1295 | 351 |
| $\phi_l$ [mm] | 7,9 | 32 | 17 | 16 | 16 | 6 |
| n [szt.] | 2 | 12 | 5 | 4 | 4 | 3 |
| **Transverse reinforcement** | | | | | | |
| $\rho_t$ [%] | 0,03 | 1,50 | 0,50 | 0,37 | 0,12 | 0,40 |
| $E_t$ [GPa] | 27,9 | 241 | 72,0 | 58,0 | 27,9 | 42,0 |
| $f_t$ [MPa] | 230 | 4140 | 1022 | 93 | 903 | 537 |
| s [mm] | 24 | 406 | 148 | 150 | 233 | 81 |
| $\phi_t$ [mm] | 4 | 20 | 9 | 8 | 8 | 3 |

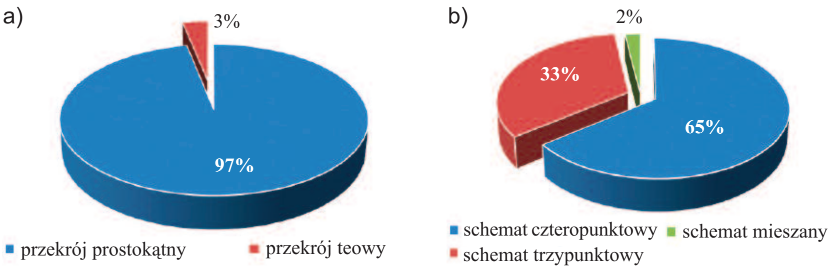

**Fig. 2. Division of beams by cross-section (a) and static schemes of elements (b)**
*Rys. 2. Podział belek wg przekroju poprzecznego (a) i schematów statycznych elementów (b)*

Only one test program [36] adopted inclined stirrups at 45°, 60° and 65° in 3 beams, while the remaining 188 test elements adopted vertical transverse reinforcement. Closed stirrups were used in 184 beams, while 7 beams used transverse reinforcement in the form of straps. Unfortunately, a lot of data is missing from the published results of the experimental work, which prevents a deeper analysis of the results obtained. Information on cracking force values can be found in only 12% of the studies.

Only a few studies [7] included comparative elements in which both longitudinal and transverse reinforcement were steel. Few publications describe single reference elements reinforced with steel bars [14], while other publications, do not include comparative analysis of FRP and steel reinforcement [17, 18, 22]. Some of the studies included a comparison of beams reinforced entirely with glass bars to beams reinforced in a mixed manner, i.e., elements with longitudinal steel reinforcement and transverse GFRP or CFRP reinforcement [4, 10, 11, 16, 32]. The vast majority of elements without transverse reinforcement (witnesses) allowed com-

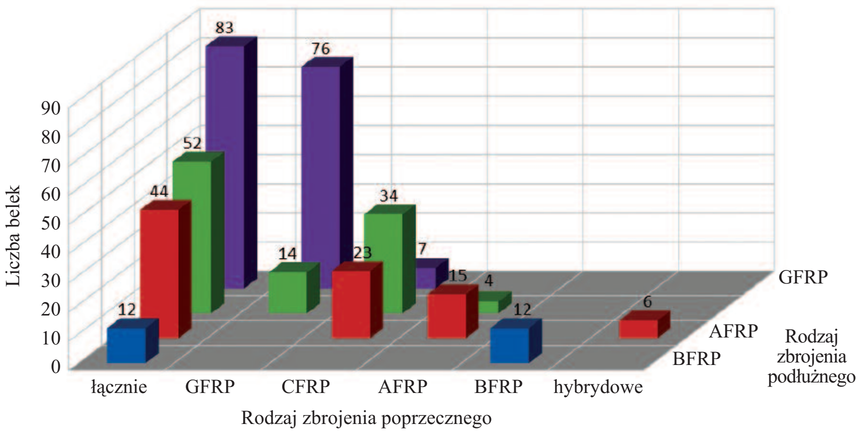

**Fig. 3. Division of beams by type of longitudinal reinforcement and type of transverse reinforcement in research elements**
*Rys. 3. Podział belek ze względu na rodzaj zbrojenia podłużnego i poprzecznego w badanych elementach*

parison of only 1 or 2 test elements reinforced with GFRP bars. Due to the lack of variable parameters in steel-reinforced beams with respect to beams with FRP bars, such analyses are very inefficient.

## Summary

A review of the literature shows that the influences of some parameters have not been clearly described, and the fact of the simultaneous influence of several variable factors does not allow the precise isolation of individual parameters, so there is a need for more experimental studies with in-depth analysis and precise description of their results, which is very often lacking in the studies publised so far.

The analysis of the research conducted so far prompted the authors to do further work to organize the state of knowledge and analyze the variable parameters affecting the shear capacity of elements with non-metallic reinforcement. Based on the collected state of knowledge, the authors analyzed the research results as accurately as possible and planned their own research program involving 10 beam elements reinforced both longitudinally and transversely with steel bars, in order to reliably relate most of the analyzed beams reinforced with GFRP bars to those reinforced with steel, thus taking into account the various variable parameters and relating them to beams with steel reinforcement [38, 39]. Most foreign standards and design guidelines for elements reinforced with composite bars are based on modifications of standards for reinforced concrete structures, so an important goal of the authors' own research is to compare elements reinforced with composite bars to those reinforced with steel, which is lacking in foreign research or comparisons between elements are not possible due to differing other variable parameters. Such a comparison of elements is crucial because elements with non-metallic reinforcement differ not only in load-bearing capacity compared to elements reinforced with traditional steel, but also show different behavior of beams after loading and failure mechanism. Beams reinforced with composite bars are characterized by larger crack opening widths, larger deflections and also a common cause of failure is the rupture of stirrups at the corners of FRP bars due to their anisotropic structure and stress concentration in the bends. In addition, the lack of analysis of the effect of the width of the compression zone of beams in previous studies prompted the authors to perform further research of their own.

## Research program

In order to analyze in detail the behavior and failure of beams reinforced in bending and shear with GFRP bars, a test program was adopted that included both beams reinforced longitudinally and transversely with composite bars. In addition, beams without transverse reinforcement were designed, as well as beams reinforced with steel bars, in order to compare the load capacity of beams reinforced with glass bars to that of beams reinforced with conventional steel. In order to analyze the effect of the amount of longitudinal reinforcement on shear, two longitudinal reinforcement ratios were assumed: $\rho_l = 2{,}9\%$ (5 $\phi$ 25) and $\rho_l = 3{,}7\%$ (5 $\phi$ 28). In order to analyze the effect of the amount of GFRP transverse reinforcement on the shear capacity of the beams, three different transverse reinforcement ratios were adopted, modifying the spacing of stirrups while maintaining a uniform stirrup diameter $\phi$ 8: $\rho_w = 0{,}16\%$ (250 mm), $\rho_w = 0{,}20\%$ (200 mm) and $\rho_w = 0{,}33\%$ (120 mm). The last variable parameter was the effect of the location of the transverse reinforcement on the load capacity. In this regard, the diameter and spacing of the stirrups were changed from $\phi$ 8 every 120 mm to $\phi$ 12 every 270 mm, thus maintaining the same transverse reinforcement ratio $\rho_w = 0{,}33\%$. Figure 4 shows the reinforcement of an example beam with a static scheme.

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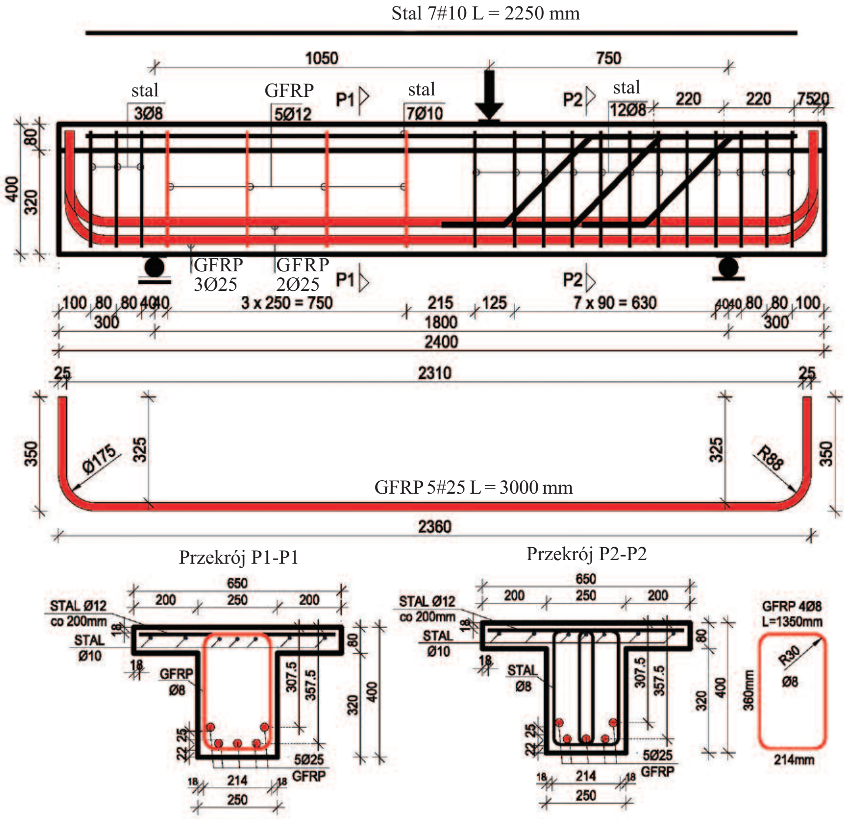

**Fig. 4. Geometry, static scheme and reinforcement of beams**
*Rys. 4. Geometria, schemat statyczny i zbrojenie belek*

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