ABSTRACT: In addition to the well-planned loads during life-cycle in usual structures, buildings such as shelters, public buildings and nuclear power plants must withstand also accidental loading. For the design of structures considering safety and economical aspects at the same time, it is necessary to consider the positive characteristics of the influence of high strain rates for the component behavior.

For reinforced concrete structures, the bond between steel and concrete takes on a key role. In the case of dynamic loading, it isn’t suffice to assess the materials and their interaction on the basis of their static behavior. While it is well known, that materials can show an increase of strength under high strain rates, the dynamic behavior can lead as much to wanted as to unfavorable effects for a reinforced concrete structure. For the design of concrete structures subjected to blast and impact, the bond behavior is particular important for the anchorage and overlapping joint of the reinforcement, where rigid bond is required to obtain short bond length. On the other hand, for the activation of load reserves with the formation of plastic hinges a ductile bond behavior is preferable.

To understand the complex phenomena in this area, there is still considerable need for research. At the University of the Bundeswehr Munich a research project on bond behavior under high loading rates is currently performed. Preliminary tests have been performed on a Split-Hopkinson-Bar in collaboration with the Ernst-Mach-Institute in Efringen-Kirchen.

KEY WORDS: Bond Model; Dynamic Increase Faktor (DIF)

1 BOND BEHAVIOR IN REINFORCED CONCRETE

1.1 Bond behavior under static conditions

In [11] the assumptions for bond in structural design have been presented and the main mechanisms for the bond between steel and concrete under static conditions have been identified.

To describe the bond behavior, the relative displacement (slip) between steel and concrete due to the transfer of forces is set into relation to the bond stress. Thereby the transferred force is assumed to be constant on the circumference of the bar. The different bond and failure mechanisms is shown in the bond-slip-diagramm (Figure 1).

![Figure 1. Idealized bond-slip-relationship.](image)

1.2 Bond behavior under high loading rates

In contrary to static bond behavior only limited research has been done about bond behavior under high loading rates. Even though the methods used by researchers are different, a tendency of increasing bond strength and stiffness with increasing loading rate for deformed bars has been realized. Results obtained from literature have been evaluated. Partially the used specimens showed a wide scatter of concrete strength. To determine the dynamic increase for bond strength, similar bond conditions have been assumed within a test series and a static reference bond strength for each specimen has been calculated with the formulas given in MC 2010:

Pull-out: \[ \tau_s = A \cdot \left( f_{cm} \right)^{0.5} \]  

Splitting: \[ \tau_s = A \cdot \left( f_{cm} / 25 \right)^{0.25} \]

A: coefficient for bond condition

Figure 6 shows the DIF for the ultimate bond strength obtained from tests conducted by different researchers. Under static conditions a coefficient of variation about 20 % for bond strength can be assumed [21]. With increasing loading rate also the variation of test-results increases.

within the range of 1.5 to 4.6 N/mm²⋅s⁻¹ has been about 1.1 to 1.7 times the static ultimate bond strength. The increase of bond strength for the lower strength concrete was higher compared to the higher strength concrete. Furthermore Shah/Hansen assumed an influence of bar diameter on increase of ultimate bond strength. In tests with hooked bars and longer embedment lengths steel fracture occurred. Under this circumstances the increase of steel strength was the decisive parameter for the loading capacity.

The tests conducted by Paschen/Steinert/Horth in 1974 with an electrohydraulic loading system with load control also showed an increase of bond strength for deformed bars with increasing loading rate. Results for deformed bars with different bond lengths, confined and unconfined specimens are shown in Figure 3. The bond-behavior of plain steel was not influenced by loading rate. For deformed bars the main mechanism of bond is based on the ribs of the steel bracing concrete consoles in the concrete surrounding the steel. Thus according to Paschen/Steinert/Horth the increasement of bond strength can be attributed directly to the increase in concrete strength. For a load duration longer than t₀ = 60 s the bond strength is decreasing. For static as well as for dynamic loading the measured transfer length of the bar was limited to lₜₗ = 15dₛ. The ultimate bond strength for specimens built with confining reinforcement to prevent splitting was higher compared to the unconfined specimens, however the dynamic increase has been lower.

Takeda carried out pull-out tests with three kinds loading rates on reinforcement in concrete prisms. A more concentrated bond stress distribution has been observed for deformed bars under high loading rates (Figure 5).

Small-scale models of reinforced concrete anchorage-bond specimens were subjected to large cyclic displacements at two rates by Chung/Shah in 1987. The reinforcing bars have
been provided with strain gages. For higher rate of loading they observed an increasing ultimate load capacity but greater damage and fewer and more localized cracks compared to slower rate of loading. While in tests of anchorage-bond specimens flexural cracks were widely distributed for slow rate, damage was due to a single wide crack for higher rate loading.

In the experiments by Yan/Mindess [20] in 1991 pull-out and push-in specimens with two different compressive strengths of concrete, two different fibres (polypropylene and steel), different fibre contents (0.1%, 0.5 %, 1.0%) and three different types of loading (static, dynamic and impact loading) have been tested. An increase of bond strength and bond fracture energy for increasing loading rates, concrete strengths and fiber contents has been noted. The mentioned factors also influenced the bond stress distribution and crack development in concrete.

Weathersby [17] conducted pull-out tests with quasi-static, dynamic and impact loading in 2003. He investigated the influence of confinement, bar deformation and bar diameter on the bond slip. He used plain and deformed bars for his tests. For impact loading he obtained a dynamic increase of ultimate bond strength about 2.0 times the static strength.

Confined and unconfined specimens with a diameter of 100 mm and bars with \( d_b = 20 \) mm have been tested on a split hopkinson bar by Solomos/Berra [14] 2010. They varied concrete strength (C25/30, C50/60) and embedment length (lb = 100 mm, 200 mm). While bond strength increased for C50/60 under high rate loading, the increase has been higher for the C25/30 specimens. The increase of ultimate bond strength for doubling the embedment length under dynamic loading was lower compared to the increase under static loading.

1.3 Parameter of bond behavior under high loading conditions

The same parameter, influencing the static bond conditions, are valid for bond behavior under high loading rates:

- Concrete compressive and tensile strength
- Position of the reinforcement in relation to the placing of concrete
- Concrete cover and confinement
- Transverse reinforcement
- Diameter of the bar and geometry of the ribs
- Stress condition in the surrounding of the bar
- Stress condition in the bar
- Cracks longitudinal to the bar
- Steel fibres

The parameter influencing the increase of dynamic bond strength as compared to static behavior are:

- Concrete compressive strength
  
  With increasing concrete compressive strength a decreasing rate dependence of bond strength has been observed [13][14][16].

- Diameter of the bar and geometry of the ribs
  
  While Weathersby [17] obtained an increase of dynamic bond strength for plain bars, in the majority of the reviewed research there seems to be no significant influence of loading rate for plain bars [12][14][16][19], the bond resistance of deformed bars increases with higher loading rates. In Shah/Hansen [13] an inverse relation of the increase in the ultimate bond strength under dynamic loads with the diameter of the bar is reported.

- Bond length
  
  In tests with long bond length steel fracture has been the main failure mechanism [4]. The stress distribution under dynamic loading is more concentrated [2][14][15][17][19]. With increasing bond length, the rate dependence decreases [14]. Structures failing in a ductile manner under static loading can fail in a brittle way by localized cracks due to concentrated transfer of bond stress for faster rate loading [2].

- Failure Type (Splitting, Pull-out)
  
  No increase in bond strength has been observed by Hansen/Liepins [4] when splitting was involved. In contrast other tests showed increased ultimate loads under dynamic loading for confined specimens failing by pull-out but a higher dynamic increase for unconfined specimens failing by splitting [12][14].

- Load Duration
  
  Only for a short loading duration the increase of bond strength results in higher load bearing capacity. With increasing load duration the bond strength decreases [12].

2 BOND MODEL

2.1 Discretisation methods

The required discretization of bond behavior depends on the purpose of a numerical simulation. Keuser [3496] defines four levels of discretization for modeling the bond behavior:

- Level 1: Modeling the bars with 2D- or 3D-elements and accurate or idealized rib geometry. For contact between steel and concrete, adhesion, friction and a loss of contact should be considered.

- Level 2: Modeling the bars with 2D- or 3D-elements and a flat surface. In addition to the mechanisms in level 1 also the mechanical interlock has to be described in a nonlinear bond-slip-relationship.

- Level 3: Modeling the reinforcement with one-dimensional elements. Because only longitudinal and no transverse extension can be calculated, effects of lateral pressure to the bond behavior have to be included in the bond model.

- Level 4: Modeling the reinforcement with a smeared or distributed model. In this level steel and bond are not modeled directly and have to be considered in a constitutive relation for a composite steel/concrete material.

It can be seen, that with increasing level more influences on bond behavior have to be included in the used bond model. On the other hand one has to assess the influence of bond for the structural behavior to choose a convenient model with an adequate accurateness for the numerical simulation. Phenomenological modeling bond elements with zero thickness or with a defined thickness for the effective bond-area are applied [6], [7], [8]. With the bond stress-slip relationship implemented in these elements pull-out of the bars can be described. For splitting failure a realistic constitutive model for the concrete surrounding the bar is required.
2.2 Influence of loading rates

Dynamic material properties often are formulated as a strain-rate $\dot{\varepsilon}$ dependent function. Because bond stress transfer is always connected to a relative displacement the dynamic bond behavior can’t be expressed in a direct relationship to the strain rate. Different ways to describe the influence of loading rates on bond behavior exists.

Vos/Reinhardt [16] formulated a bond-stress-rate $\dot{\tau}$ dependent mathematical description for a range of the slip from $0 < s < 0.2$ mm and relative rib area $0.065 < f_R < 0.1$ of the bar.

$$\eta = 0.7 \cdot (1 - 2.5 \cdot s) f_c^{0.8}$$

Greulich [3] developed the bond model GReCon for reinforced concrete under high dynamic loads. He assumes a direct relationship between the increasement of bond strength and concrete strength for high strain rates. He proposes a hyperbolic function to describe the dynamic bond behavior.

The dimensionless strain rate $\dot{\varepsilon}^*$ refers to a reference strain rate $\dot{\varepsilon}_0 = 1.0$ s$^{-1}$.

$$DIF(\dot{\varepsilon}^*) = \left[ \tanh(\log(\dot{\varepsilon}^*) - 2.0) \cdot 0.4 \right] \left[ \frac{3.58}{2.29} - 1 \right] + 1 \cdot 2.29$$


$$DIF\left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) = 0.5 \cdot \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{0.13} + 0.9 \quad \text{with } \dot{\varepsilon}_0 = 1.0 \text{ s}^{-1}$$

3 DIFFERENTIAL EQUATION

3.1 Differential Equation

In [9] Martin shows the differential equation for bond between steel and concrete under the assumption of elastic behavior.

$$\sigma_t(x) + d\sigma_t(x) = \sigma_t(x) + \frac{\sigma_t(x)}{E_s} \cdot \sigma_t(x)$$

Figure 7. Differential element

A change of relative displacement between steel and concrete is equivalent to the difference of their respective strains.

$$\frac{ds(x)}{dx} = \varepsilon_t(x) - \varepsilon_t(x) = \frac{\sigma_t(x)}{E_s} - \frac{\sigma_t(x)}{E_c}$$

With $n = E_s/E_c$ and $\mu = A_s/A_{st}$ the following equation can be developed:

$$\frac{ds(x)}{dx} = \frac{\sigma_t(x)}{E_s} \cdot (1 + n\mu)$$

A change of tensile force in a circular bar equals:

$$\frac{d\sigma_t(x)}{dx} = \frac{4}{d_s} \tau_b(s(x))$$

With equation (9) and by differentiating equation (8) one gets the differential equation for bond-slip:

$$\frac{d^2s(x)}{dx^2} = \frac{4}{d_s \cdot E_s} \cdot (1 + n\mu) \cdot \tau_b(s(x))$$

3.2 Numerical approach

The solution of the differential equation has been approximated with Runge-Kutta method. In this paper the bond stress-slip relationship given in MC2010 with equation (3) to consider the influence of loading rate has been applied.

In 1.2 and 1.3 an overview of research about bond under high loading rates and the assumed parameter of rate influence on bond behavior are given. From Experiments a more concentrated force transfer length and brittle failure in anchorages or plastic hinges is reported. The numerical model shows due to the increased bond strength also the reduced length for dynamic loading (Figure 8). This effect is also known for high strength concrete where not only the bond behavior but also the failure mechanisms are different.

Figure 6. DIF for ultimate bond strength

Figure 6 shows the different approaches with the experimental results found in Literature.
Figure 8. Transfer length for static and impact loading

Figure 9 shows the influence of the diameter and the embedment length of the reinforcement bar. The increase of each of these two parameters leads to an decrease of the DIF. This effect is due to the slip dependence of the used formula by Vos/Reinhardt.

Figure 9. Decrease of DIF with increasing bar diameter and embedment length

By using the differential equation for elastic behavior shown in 3.1 combined with the DIF-formula valid for a range of slip up to 0.2 mm developed by Vos/Reinhardt it is possible to show some of the in experiments observed effects. To simulate also anchorage and plastic hinges in an ultimate limit state it is important to include also the non-elastic range with post-yield behavior of steel.

3.3 Diskussion

According to Bigaj [1] the stress-slip relationship in MC90 underestimates the bond stiffness in the range of increasing bond stress with increasing slip, but overestimates the bond stress in the post-yield range compared to results obtained in her experiments. Different confinement and bond conditions can explain this differences. She also notes, that the change in the bond stress-slip relation due to the yielding of steel have to be considered and an extrapolation of empirical relations based on NSC to HSC may lead to incorrect results.

With the approach shown in 3.2 it is possible to apply a bond-slip relation for high loading rates on longer embedment lengths. The observed influence of bond length in experiments also occurred in the numerical approach. The relationship given by Vos/Reinhardt [16] is suitable for application with small deformations. Structures exposed to explosive or impact loading can fail in a brittle manner due to increased bond strength and localizing cracks. To describe this effect it is important to consider the influence due to yielding of steel as well as loading rate on ultimate bond stress and the post yield range.

4 EXPERIMENTS

To validate the bond-model tests will be performed in collaboration of the University of the Bundeswehr and the Fraunhofer Ernst-Mach-Institute. The concept of the preliminary tests has already been described in [11]. A configuration based on the principle of an indirect tensile loading induced by a Split-Hopkinson-Bar device has been used (Figure 10).

Figure 10. Schematic Test Configuration SHB

The configuration is basically suitable for very short bond length, but its limited by the possible dimensions of the test specimen and the tensile strength of the concrete.

5 CONCLUSIONS

The interaction of steel and concrete is essential for the design of concrete structures. The increase of bond strength can lead to different behavior of reinforced concrete structures compared to static behavior.

The requirement on a bond model depends on the choosen discretization level. To simulate dynamic behavior of structures including bond behavior in the ultimate limit state the influence of concrete strength and slip with a range up to the post-yield of steel is necessary.

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