# A NEW SPRING MODEL FOR CONCRETE CONE FAILURE OF ANCHORAGES UNDER TENSION

# EIN NEUES FEDERMODELL FÜR ZUGBEANSPRUCHTE GRUPPEN-BEFESTIGUNGEN BEI DER VERSAGENSART BETONAUSBRUCH

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## SUMMARY

The design of anchorages according to the current codes and guidelines is limited to rectangular configurations and a sufficiently rigid base plate is required. However, due to technical, functional or architectural requirements, anchorages are also used in industry, for which the design is not covered by the current provisions. Furthermore, with the current design provisions, it is rather difficult to ensure that a sufficiently rigid base plate is used, which may lead to unsafe design solutions (lower calculated anchor forces than in reality). This paper gives an overview of a new nonlinear spring model for realistic assessment and design of tension loaded anchor groups in case of concrete cone failure. The concept of the spring model is based on the assumption that within an anchor group, anchors resist the tension forces, while the compression forces are transferred directly by the base plate to the concrete. Nonlinear tension-only springs are used for modelling the anchor behaviour. A tributary area approach for individual anchors takes into account the influence of spacing and edge distance, while the influence of eccentricity and base plate stiffness is automatically accounted for through nonlinear analysis. The base plate is modelled using finite solid or shell elements to realistically consider the base plate stiffness and attachments including possible stiffeners. With this model, it is possible to design and assess anchor groups, which are currently beyond the scope of the design provisions without requiring the use of a sufficiently rigid base plate.

## ZUSAMMENFASSUNG

Die Bemessung von zugbeanspruchten Befestigungen in Beton nach den aktuellen Richtlinien hat viele wesentliche Einschränkungen. Die Bemessung ist auf rechteckige Ankeranordnungen beschränkt und setzt die Verwendung einer ausreichend steifen Ankerplatte voraus. Definitionen und Vorschriften zur Bestimmung einer ausreichend steifen Ankerplatte sind in den Vorschriften jedoch nicht angegeben. Aufgrund technischer und baulicher Anforderungen werden jedoch auch Befestigungen, bei denen die Bemessung durch die aktuellen Vorschriften nicht abgedeckt ist, in der Baupraxis ausgeführt. Darüber hinaus ist es bei den derzeitigen Bemessungsvorschriften eher schwierig sicherzustellen, dass eine ausreichend steife Ankerplatte verwendet wird, was zu unsicheren Bemessungslösungen führen kann (geringere berechnete Ankerkräfte als in der Realität). Ziel dieses Beitrags ist es, einen Überblick über das neue nichtlineare Federmodell zur realistischen Bemessung und Bewertung von zugbeanspruchten Gruppenbefestigungen bei Betonausbruch zu geben. Das Konzept des Federmodells basiert auf der Annahme, dass innerhalb einer Ankergruppe die Zugkräfte von den Befestigungen aufgenommen werden, während die Druckkräfte direkt durch das Anbauteil in den Beton eingeleitet werden. Um das Dübelverhalten zu modellieren, werden nichtlineare Federn verwendet. Der Einfluss des Bauteilrandes und der benachbarten Befestigungen wird durch einen Ansatz für die Flächenaufteilung berücksichtigt. Die Ankerplatte wird mit finiten Solid- oder Schalenelementen modelliert, um die Steifigkeit der Ankerplatte sowie Lastumlagerungen zwischen den benachbarten Befestigungen einschließlich möglicher Versteifungen der Ankerplatte realistisch zu betrachten.

KEYWORDS: Spring model; anchor group; concrete cone failure; tension loading; non-linear anchor spring; base plate stiffness

## 1. INTRODUCTION

The current design recommendations for tension loaded anchorages given in the codes and guidelines (EN 1992-4 [1], ETAG008 [2], fib Bulletin 58 [3], ACI 318-14 [4]) are limited in scope to rectangular anchor groups with a maximum of three anchors in a row and a requirement to have a rigid base plate is given. However, the criteria for the judgement of the rigid base plate are currently not quantified and only qualitative guidelines are given. It is well known that if the base plate is not rigid, the assumption of using a rigid base plate can lead to unsafe design solutions. Furthermore, several assumptions are considered currently, which may render the design conservative such as eccentric loading and/or vicinity of the concrete edge. Experimental investigations in Bokor et al. 2019a

[5] showed that the current provisions yield more conservative results with increasing the eccentricity in the case of anchor groups with three anchors in a row or when the eccentricity is about both the orthogonal axis (biaxial eccentricity). Moreover, anchorages placed close to a concrete edge and loaded eccentrically in tension are not considered with sufficient accuracy [5]. The limitations call for a new design method that can consider arbitrary base plates and loading positions without the requirement of a rigid base plate or rectangular anchor pattern.

## 2. NONLINEAR SPRING MODEL FOR CONCRETE CONE FAILURE

### 2.1. THE CONCEPT

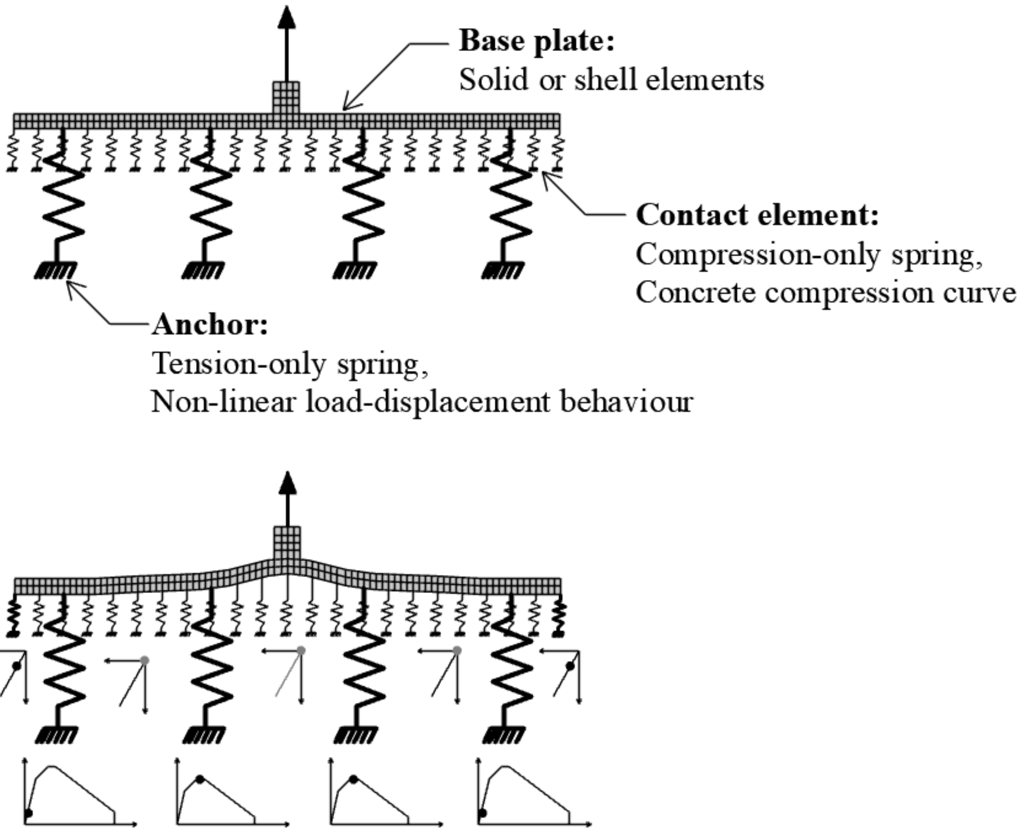
A generally applicable spring model for evaluation and design of tension loaded anchor groups, which fail due to concrete cone failure was proposed and discussed in Bokor et al. 2019b [6]. The spring model includes components such as anchors, base plate and contact between concrete and the base plate. The concept of the model is based on the assumption that within an anchor group, only the anchors resist the tension forces, while the compression forces are transferred directly by the base plate to the concrete. This is realized in the model by characterizing the anchor behaviour using non-linear tension-only springs, while the contact between the base plate and concrete is modelled using compression-only springs (Fig. 1).

Considering the nonlinear anchor behaviour is essential to account for a realistic force distribution among the anchors of the group. In this way, as an anchor loses stiffness by attaining high forces, the forces can be distributed to the other anchors of the group based on the stiffness conditions among the adjacent anchors and the base plate. In order to account for the influence of vicinity of the concrete edge and the neighbouring anchors (Fig. 1b), a new tributary area approach is applied in the spring model, which was developed based on a large number of experimental investigations [5] and is extensively discussed in [6].

The base plate with attachments and possible stiffeners are modelled using finite solid or thick shell elements (applying thick-plate formulation following the Mindlin-Reissner plate theory) to realistically consider the stiffness conditions within the anchor group. The spring model does not aim to define requirements for a sufficiently stiff base plate.

Once the model for the anchor group is developed using the tension-only springs, the base plate and the compression only springs, a displacement-controlled non-linear static analysis is performed (using secant stiffness method).

The following output is obtained from the nonlinear analysis: the load-displacement curve of the anchor group, load-displacement curves of individual anchors, deformed shape of the base plate and the stresses developed in the base plate. Moreover, a step-by-step performance check for every component of the model is available. A detailed description of the model and of the analysis is given in [6].




a)

b)

*Fig. 1: Spring model for anchor groups against concrete cone failure a) unloaded model, b) centric tension load is applied on the model*

## 2.2. ANCHOR SPRING CHARACTERISTICS

The most important element, which should be defined for a spring model of tension loaded anchor groups, is the spring characteristics of the anchors. In this model, the anchor behaviour is characterized by the nonlinear load-displacement curve of the tension loaded anchor (Fig. 2a), which in turn depends on the failure mode such as steel failure, pullout failure or concrete cone failure. This paper addresses the anchorages governed by concrete cone breakout failure mode. In the new model, the nonlinear load-displacement curves are idealized using a penta-linear format (Fig. 2a), where the characteristic points A-F data are defined by data pairs of load and displacement values (Fig. 2b). The values $k_1$ - $k_4$ are secant stiffness values corresponding to the characteristic points. Details about the idealization of load-displacement curves are given in [6]. In the spring modelling approach, these idealized load-displacement curves can be directly used as spring characteristics for the anchors provided the anchor spacing is equal or greater than the critical spacing ($s \geq s_{cr}$) as shown in Fig. 3. However, if the anchor spacing is smaller than the critical spacing ($s < s_{cr}$), modifications on the idealized curve should be performed (Fig. 3). The critical spacing is typically taken as three times the effective embedment depth of the anchor ($s_{cr} = 3h_{ef}$).

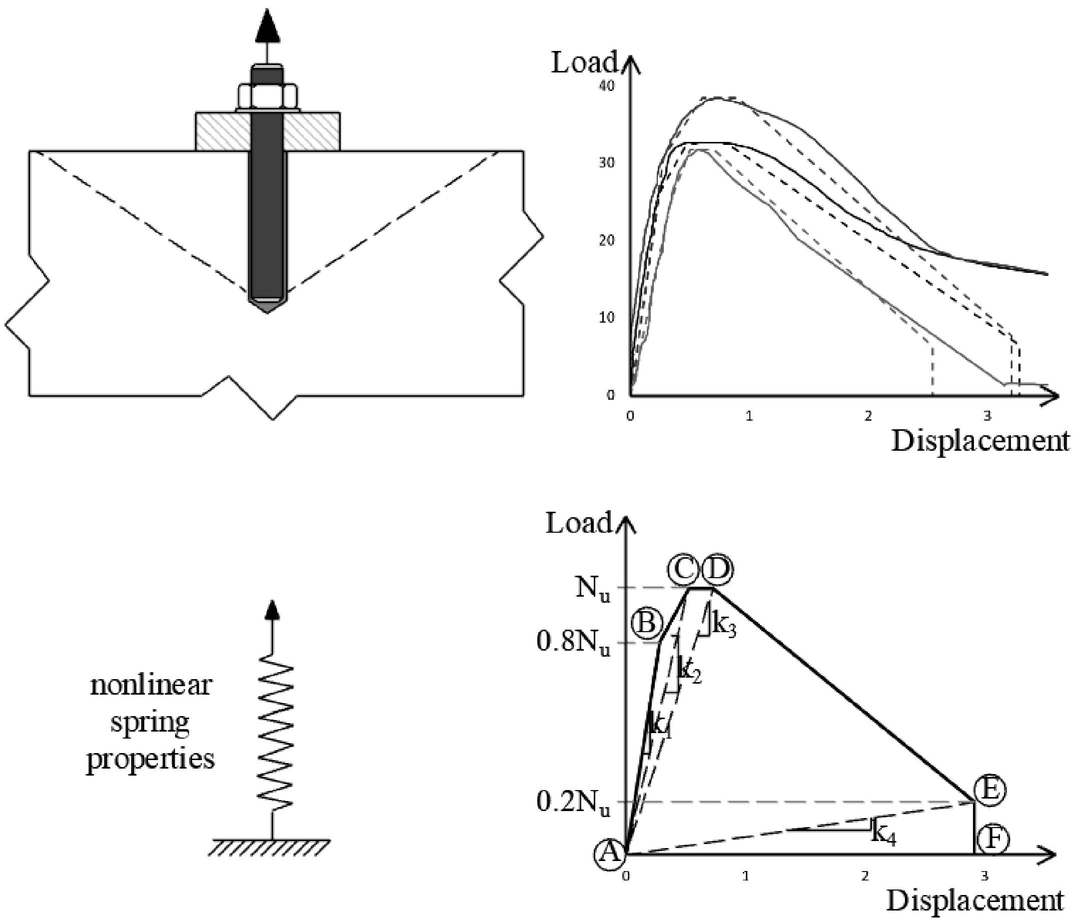



*Fig. 2: a) Load-displacement curves and idealised curve of single anchors failed due to concrete cone failure, b) spring characteristics of the corresponding single anchor*

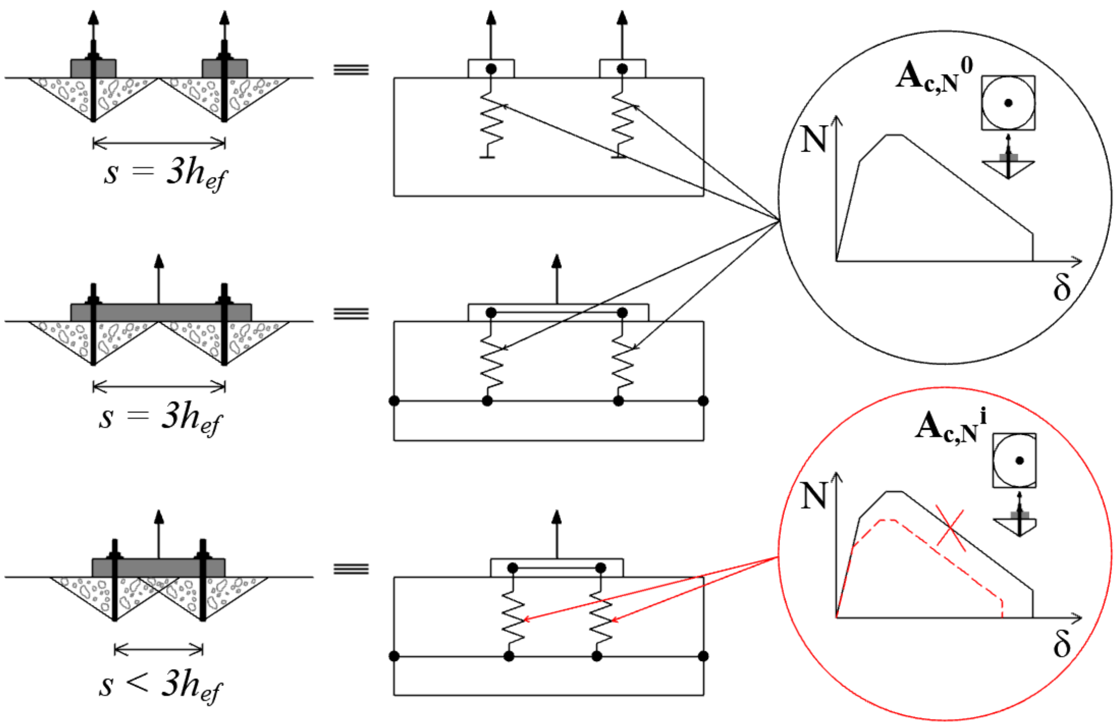



*Fig. 3: Spring characteristics for single anchors with s = 3$h_{ef}$ and for individual anchors of 2 x 1 anchor group with s = 3$h_{ef}$ and s < 3$h_{ef}$*

## 2.3. TRIBUTARY AREA APPROACH

In case of anchor groups with anchor spacing smaller than the critical spacing (s < 3$h_{ef}$), the concrete breakout bodies and consequently, the theoretical concrete cones are partly overlapping and the capacity of the group is less than the sum of the corresponding single anchor capacity (Fuchs et al. 1995 [7]). Consequently, the spring characteristics of the individual anchors must be modified to account for the reduced resistance due to group effect and the overlapping concrete cones (see Fig. 1b and Fig. 3). This is done by applying the tributary area approach, which is extensively discussed in [6] and the experimental evidence is given in [5].

In the spring model, two main postulates are considered to obtain the modified spring characteristics to account for the vicinity of concrete edge and neighbouring anchors:

***1) The failure load of the individual anchors within the group is reduced according to Eq. (1)***

The mean failure load of an i$^{th}$ anchor within an anchor group, $N^i_{Rm,c}$ influenced by the neighbouring anchors or close edge is given as

$$N^{i}_{Rm,c} = N^{0}_{Rm,c} \cdot \frac{A^{i}_{c,N}}{A^{0}_{c,N}} \tag{1}$$

Where,

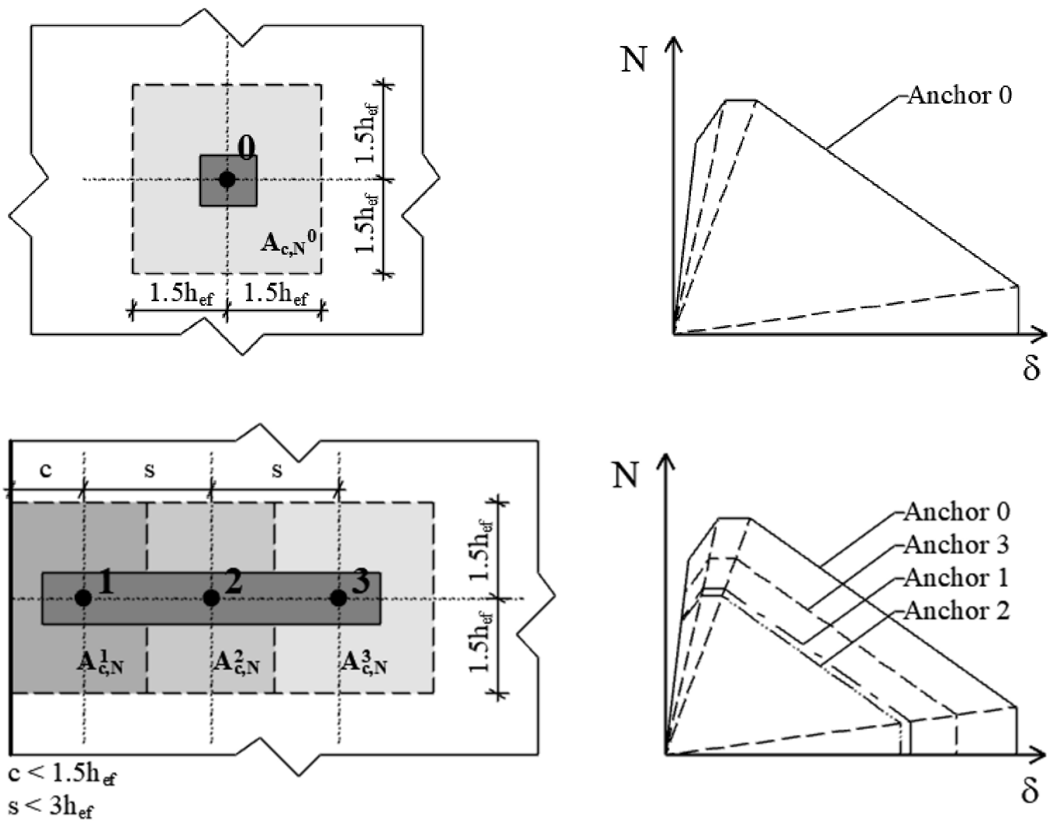
$N^{0}_{Rm,c}$ is the basic concrete cone breakout strength of a single anchor not influenced by the neighbouring anchors or close edge

$A^{i}_{c,N}$ is the tributary projected area assigned to the anchor considering the distance from the adjacent anchors and the edge distance

$A^{0}_{c,N}$ is the reference projected area of a single anchor with a distance from all the edges equal to or greater than the critical edge distance $c_{cr,N} = 1.5h_{ef}$

2) ***The tributary area assigned to an anchor does not influence the stiffness of the anchor ($k_1$ - $k_4$ in Fig. 2b). Consequently, the stiffness values for each characteristic point remain unchanged.***

Fig. 4 gives an example of the application of the tributary area approach and of the determination of the reduced load-displacement curves of individual anchors of a group. In general, the tributary projected area, which is assigned to an anchor, is limited either by the real concrete edge or a virtual edge considered at a distance of half the spacing to the adjacent anchor but not more than $1.5h_{ef}$. For an anchor group of 3 x 1 configuration placed close to an edge (Fig. 4), the tributary area is limited: (i) for Anchor 1 by both a close concrete edge and by the adjacent anchor, (ii) for Anchor 2 by the adjacent Anchors 1 and 3 and (iii) for Anchor 3 by the neighbouring anchor on the left side (Fig. 4b). When the tributary areas are calculated, the spring characteristics for the individual anchors can be determined by scaling the basic spring characteristics (obtained from reference tests), taking into account the Postulates 1 and 2. The ultimate load is reduced according to Equation (1), keeping the stiffness values for each characteristic point unchanged. With this, the tension-only anchor springs are obtained, and the model for the anchor group can be developed using the tension-only springs, the base plate and the compression only springs. Subsequently, a displacement-controlled nonlinear static analysis is performed. Finally, the load-displacement curve of the anchor group as well as of the individual anchors can be plotted. Applying the presented approach, the load-displacement curves obtained from the spring model compared to experimental results are given in Fig. 5 for an eccentrically loaded anchor group of 1 x 3 configuration placed close to the concrete edge. It can be seen that the spring model is able to describe the behaviour of the investigated anchor group very well. Furthermore, the obtained results highlight the fact that when anchor groups are placed close to the concrete edge and are loaded eccentrically in tension, it makes a considerable difference whether the eccentricity of the load is away or close the edge. This is due to the fact that anchors, which are closer to the point of load application, take up higher forces than the other anchors of the group. However, if the higher loaded anchors are close to the concrete edge, the resistance of these anchors is limited due to the vicinity of the concrete edge and therefore, the group capacity is also reduced. This behaviour is currently not captured by the design. However, it is automatically accounted for in the spring model by using the tributary area approach and performing nonlinear analysis. More details about the calculation and experiments can be found in [6] and [5] (test series G22 and G23).




a)

$$\mathbf{A}_{c,N}^{1} = (c + 0.5s)(3h_{ef})$$

$$\mathbf{A}_{c,N}^{2} = s(3h_{ef})$$

b) $$\mathbf{A}_{c,N}^{3} = (0.5s + 1.5h_{ef})(3h_{ef})$$

*Fig. 4: Example for the definition of the tributary areas and scaling of the idealized curve a) reference projected area, b) projected area of an $i^{th}$ individual anchor of the group*

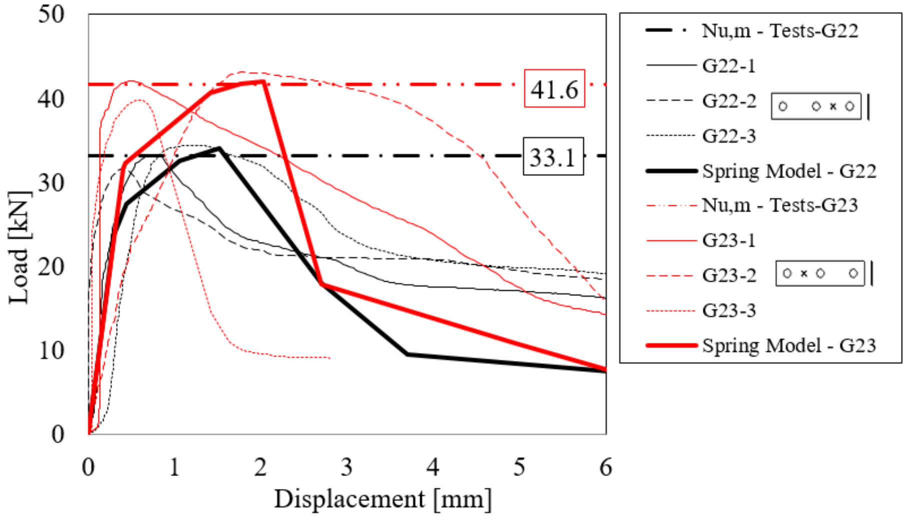



*Fig. 5: Results obtained from the spring model compared to experiments [5, 6]*

## 3. VALIDATION AND ADVANTAGES OF THE SPRING MODEL

The nonlinear spring model [6] was validated for anchor groups of rectangular and non-rectangular configurations with rigid and flexible base plates. In [6], the results of 22 spring models of different anchor groups were compared with the corresponding 65 experimental results from [5]. The experiments included anchor groups placed far from or close to the concrete edge subjected to centric or eccentric tension loading, anchor groups with biaxial eccentricity, anchor groups with not sufficiently rigid base plates, anchor groups of L-shaped, hexagonal, triangular configurations. The mean value of the ratio of failure loads obtained from the experiments and from the spring model, $N_{u,test}$ / $N_{u,spring.model}$ is 1.0 and the coefficient of variation is 11%. The spring model is able to describe the behaviour of rectangular and non-rectangular anchorages very well.

By using the nonlinear spring model, the design of anchor groups, which are not covered or not considered with sufficient accuracy according to the current provisions, is possible. Furthermore, the complete nonlinear behaviour of the individual anchors within a group is considered and due to this, the force distribution and redistribution among the anchors is accounted for in the model. There are no requirements for additional modification factors to consider the influences of the vicinity of the concrete edge or eccentricity because these influences are automatically accounted for by performing nonlinear analysis using the real stiffness of the base plate and the complete nonlinear behaviour of the anchors by the springs. More details about the development and the nonlinear spring modelling approach can be found in [6], and experimental evidence is given in [5].

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