Ductility of high performance joint between HSC column and NSC flat slab

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Abstract

Modern trends in design of high performance structures include development of new approaches for materials and elements, which can more easily resist a wide range of external actions. For example, using classical properties of concrete, like its resistance to compression, should be most effective. In this context it is possible to mention high performance two-layer beams with high strength concrete (HSC) in compressed zone and normal strength concrete (NSC) in the tensile one. This idea was further developed in the frame of the current research from the viewpoint of column – flat slab high performance joint. The joint consists of HSC columns and NSC flat slab. In this case providing appropriate joint ductility becomes one of the most important design requirements, because ductility defines the ability of a structure or its elements to absorb energy by plastic deformations. This study was aimed at complex experimental and theoretical investigation of such joints ductility. Essential contribution to the joint's ductility can be obtained due to the slab's confining effect. It was demonstrated that the ductility depends on the joint's confining effect in two horizontal and vertical directions. The influence of slab load intensity and slab reinforcement ratio on the joint's ductility is also taken into account. It is demonstrated that the effects of the ratio between the slab thickness and the column's section dimension, as well as the presence of ties in the joint, on ductility are significant too.

Keywords: ductility, high performance concrete, flat slab-column joint, two-layer beam, fibered concrete.

WIT Transactions on The Built Environment, Vol 112, © 2010 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM100031

1 Introduction

Ductility is one of the most important design parameters, especially for structures, subjected to dynamic loads. It defines the ability of a building or its elements to absorb energy by plastic deformations before damage is caused to the structure. Up to the end of the 20^{th} century ductility was defined in a qualitative manner. Basic principles for structural design, using ductility demands, were described by Chopra [1]. The method is most suitable for structural elements made of elastic – ideal plastic materials, like steel. Iskhakov showed that besides the traditional "stress – strain" evaluation of RC elements, energy dissipation design must be carried out [2].

Further, an analytical method, enabling estimation of the plastic energy dissipation (PED) ability and ductility of RC sections, was proposed [3]. According to this method, an RC element's energy dissipation ability was defined as total plastic energy, dissipated in the section, undergoing gravitational and dynamic loads. This ability corresponds to a certain ductility, which is taken into account in the design procedure.

Behaviour of RC structures considerably depends on their elements' performance. Following this approach, the most important factors, affecting the section energy dissipation, are: over-reinforcing, symmetric reinforcement, the section reinforcement maximum area, gravitational stresses, etc. Cyclic nature of most dynamic forces yields corresponding changes in the sign of the reinforcement stresses. Hence the compressive zone is periodically over-reinforced and the tensile one is poorly reinforced. In this case the reinforcement contributes little to the section's energy dissipation.

For taking into account the influence of structural ductility, modern codes define the dynamic forces reduction coefficient according to the type of the building's structural system [4], [5]. However, such approach is not enough accurate, as all structural systems are divided into three groups: RC frames, steel frames and other structures. That is why ductility of each part of a structure (for example, a column – flat slab joint, investigated in this paper) should be considered separately. Elements, forming such structural parts, contribute to its ductility. Hence, each structural element should also have proper ductility.

Two-layer beams with fibered high strength concrete (HSC) in the compression zone and normal strength concrete (NSC) in the tensile one [6] represent one of such solutions, providing required structural ductility. It was shown that such beams are effective, if their sections compressed zone correspond to a rather big bending moments. NSC, used in the section tensile zone, contributes additionally about 20% to the section's plastic energy dissipation, compared to one-layer HSC beams [7]. Using steel fibres (SF) in the compressed zone significantly increases the ductility of the whole section. Fibres have little effect on beams elastic deflections, but increase the overall PED potential of the section. The role of fibres for transverse tensile deformations absorption is similar to that of tensile reinforcement for longitudinal tensile stresses absorption in usual RC structures [6].

Pre-stressing the tensile zone of the two-layer beams yields further improvement in their performance [7]. A design method for such beams, consisting of steel fibered HSC in compressed zone and pre-stressed NSC in tensile one was proposed. It follows that two-layer fibered HSC/NSC elements become high performance ones. Summarizing the above described methods, the main principles, required for getting high performance bending elements, were formulated.

Problems of energy dissipation and ductility have been also studied by other researchers. Karabinis and Kiousis [8] have investigated the lateral confinement of rectangular concrete columns and its influence on strength and ductility [8]. The solution was based on coupling of the elastic-plastic relations for concrete and steel, and compatibility of deformations of the concrete core and the transverse reinforcement. The ability of the method to predict the response of confined compression members was demonstrated based on experimental results.

Results of experimental investigations on elements' ductility were also reported in the last years. Moretti and Tassios carried out tests on eight full-scale RC short columns, subjected to compression and cyclic shear displacements [9]. Two different layouts of main reinforcement were tested: conventional (longitudinal) and a combination of longitudinal and diagonal reinforcement in two directions. It was shown that the presence of such reinforcement improved the specimens' ductility, but not to the level, required by current codes.

Wu has studied over-reinforced RC beams and proposed a new scheme, providing their ductility through compressive yielding instead of tensile one [10]. The effectiveness of the new scheme was illustrated by experimental testing of RC beams.

A simple analytical model for estimation of ductility and deformation capacity of fibre reinforced polymers (FRP) retrofitted circular bridge columns was developed [11]. The efficiency of this method was verified by comparing numerical and experimental results. It was found that steel reinforcement ratio, axial load ratio and jacket rupture strain define the ductility of FRP retrofitted columns.

The next important problem that has been studied is quantitative definition of structural ductility. Polak [12] carried out experimental and analytical research on providing adequate ductility to reinforced concrete slab-column connections. The importance of ductility for resistance against overloading and the role of transverse reinforcement in providing ductility were discussed and also demonstrated experimentally.

Shah and Ribakov [13], [14] have studied the confining effect and load transfer mechanism of HSC columns through an NSC slab layer. They have carried out tests of interior type slab-column joints and proposed to use a mechanics of materials approach for calculation of the effective concrete strength of such joints. Experimental results that were obtained in their works, are used in the current paper for analysis of HSC column - NSC slab joint ductility. It allows getting a quantitative value of the joint ductility that will be analysed below.

2 Ductility of column - flat slab joint's elements

Ductility of a column – flat slab joint depends on the contributions of all elements, forming the joint (Figure 1). Stress-strain relations in compressed RC elements under monotonically increasing deformations were studied previously [3]. This approach is suitable for elements 1 and 2 in Figure 1. An analytical method, enabling estimation of plastic energy dissipation ability and ductility of RC sections, was proposed. In this method, an RC element's energy dissipation ability was defined as total plastic energy, dissipated in a section. This ability corresponds to a certain ductility, which was recommended to be taken into account in design.

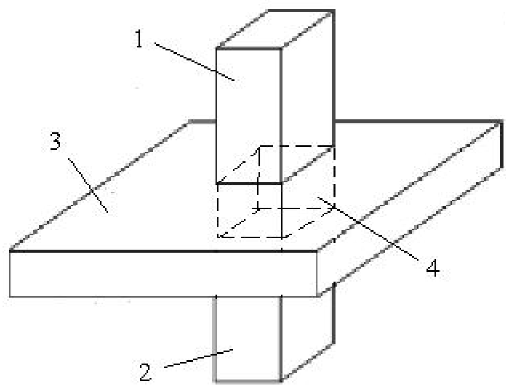

Figure 1: A column - flat slab joint: 1 - upper HSC column part, 2 - bottom HSC column part, 3 - NSC flat slab, 4 - common NSC zone (following [15]).

For bending elements, like a flat slab (position 3 in Figure 1), with reinforcement in the compressed zone also, it was shown that the total PED equals to a sum of PED, contributed by compressed concrete, tensile and compressed reinforcement [3]. It is a basis for calculation of ductility in a case, when the plastic tensile strain of the steel and the plastic part of the concrete compressive strain become critical simultaneously. Finally, the RC element's PED capacity was formulated. It allows obtaining quantitative ductility values for each type of RC elements – under compression, bending or cyclic loads. However, interaction between the elements was not studied.

The common zone between elements 1, 2 and 3 (see Figure 1) is in a complicated strain-stress stage due to confinement from element 3 and additional reinforcement in the joint, difference in materials' properties of the columns, flat slab and joint itself.

Common behaviour of four elements, forming a column – flat slab joint, was investigated experimentally [13], [14]. The results of the tests are used in the current study for analysis of the joint's ductility.

3 Test setup and general description of specimens' behaviour

Column concrete strength varied from 23 MPa to 120 MPa, representing NSC and HSC, respectively. All the columns (positions 1 and 2 in Figure 1) were 200×200 mm in size. Longitudinal and transverse column reinforcements consisted of ∅14–16 mm and ∅6–10 mm steel bars, respectively.

The slab and joint concrete strength (positions 3 and 4 in Figure 1) has ranged from 13 MPa to 46 MPa (NSC). The slabs were 800×800 mm with thickness from 120 to 240 mm. Reinforcement at the top and bottom of the slab consisted of ∅8–15 mm bars. More detailed information about the tested specimens is shown in Figure 2.

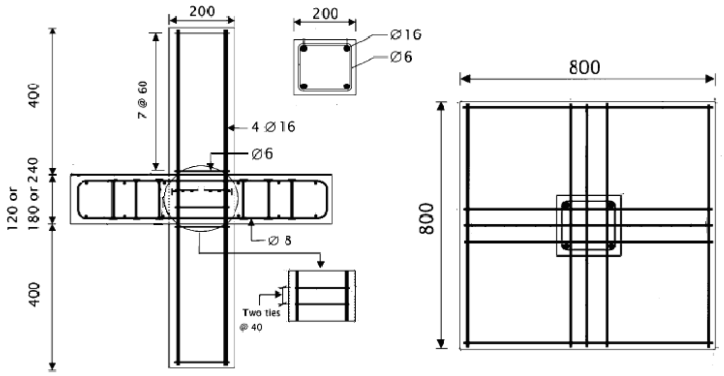

Figure 2: Reinforcing details and dimensions of the tested specimens (following [13]).

For improving the confined conditions of the joint region, surrounded by overhanging slab portions, two uniformly spaced hoop bars were placed in the joint centre. Strains in column (at top and bottom) and slab were measured by linear variable displacement transducers (LVDT), located on steel bars, as well as on column and slab concrete surfaces. Strain gauges were also located at the mid-depth of slab and on the square ties, provided in the centre of the joint region.

All the specimens were tested in axial compression, with or without slab loading, using universal testing machines with minimum capacity of 6000 kN. Slab load was either held constant or increased gradually in steps until the specimen failed.

For specimens that failed due to crushing inside the joint, a considerable softening behaviour was observed. For failure, occurred in lower columns, a sudden and slightly brittle behaviour was observed, while the upper column exhibited a ductile behaviour.

The longitudinal column bars yielded at an average strain of about 0.0025, and cover concrete damage began at an average strain of about 0.0026. The longitudinal bars in column and joint region yielded under different load intensities. In the loaded slab specimens the upper column's spalling arrived earlier than lower one. This was due to complicated confined strain-stress condition in the joint. As the slab load increased, the slab bent down and the column faces started loosing its contact with the upper half of the joint.

The column - flat slab joint's ductility depends on the following factors:

- quantitative value of joint's confining effect in two horizontal directions, offered by the surrounding slab, and vertical direction, offered by the column;
- slab load intensity;
- slab reinforcement ratio;
- aspect ratio, h/c (where h is the slab thickness and c is the column's section dimension);
- presence of additional ties in the joint.

As it was mentioned above, the tested column – flat slab joints were made of two different materials – HSC columns, NSC slab and common zone. Hence, for analysis of such joints' ductility a previously developed by the authors approach may be used [7]. This approach was developed for two-layer fibered concrete beams, using conventional methods for composite elements. The compressed zone of such beam section is made of HSC, and the tensile one – of NSC. Following this approach, if the calculated ductility of the joint does not satisfy the design requirements, it is proposed to add fibres in columns, above and below the common zone. According to the modern code provisions [5], the sensitive column length near the joint is ± 1.5 c, where c is the larger column section's dimension. That is why the length of the zone, in which fibres are proposed to be added, is also recommended to be at least ± 1.5 c.

4 Discussion of experimental results

Figure 3 shows the column load vs. average joint transverse strain for different cases:

- h/c = 0.6, 0.9 and 1.2;
- P_{slab} = 442, 459, 624 and 871 kN, where P_{slab} is the load, applied in the corners of the slab.

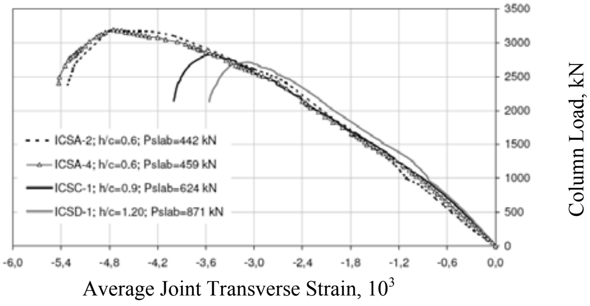

Figure 3: Effect of slab load on column – flat slab joint behaviour (following [13]).

As it follows from Figure 3, increasing the h/c twice yields a decrease of about 1.5 times in the joint's transverse (vertical) strains. It is because a thicker slab has higher bearing capacity. Behaviour of all specimens' types from the transverse strains viewpoint is similar until the loading capacity of the weakest specimen type is reached (see ICSD – 1 in Figure 3). Behaviour of specimens' types ISCA – 2 and ISCA – 4 is very similar. The difference between these two specimens' types is that the last one has additional uniformly spaced lateral ties in the joint region. But, as it follows from the figure, the ties almost do not affect the vertical strains.

Figure 3 also demonstrates that for all specimens that were tested, concrete in the joint behaves elastically until the compression strain $\varepsilon_c = -2.4 \times 10^{-3}$. For specimens with low confining effect (ICSC-1 and ICSD-1) plastic deformations are until $\varepsilon_c = -3.9 \times 10^{-3}$ and $\varepsilon_c = -3.6 \times 10^{-3}$ respectively. For the other two specimens' types (ICSA-2 and ICSA-4) the plastic deformations are -5.3×10^{-3} and -5.4×10^{-3} respectively.

Based on the above mentioned elastic and plastic deformations, ductility parameters were calculated as $\mu = 1 + E_{pl} / E_{el}$. Here E_{pl} and E_{el} are energy portions, dissipated by plastic and elastic deformations, respectively. The calculated ductility parameters are shown in Table 1.

Table 1: Calculated ductility parameters of column – flat slab joint.

Specimen type (according to Figure 3)	ICSA-2	ICSA-4	ICSC-1	ICSD-1
h/c	0.6	0.6	0.9	1.2
Maximum bending moment in the joint, kN m	88.4	91.8	124.8	174.2
Maximum column load, kN	3250	3200	2850	2750
Eccentricity, cm	2.7	2.9	4.4	6.3
Ductility parameter, μ	4.44	4.32	2.72	2.25

Ductility increases proportionally to the decrease of the negative bending moment, because for higher bending moments, acting in the joint, the flat - slab confining effect is lower. A similar relation between the ductility parameter and *h/c* is evident.

The common zone between columns and slab (position 4 in Figure 1) is confined by the surrounding slab. It is was previously shown that in a common case confinement can increase the element's ductility up to two times, if the slab is unloaded [7]. However, slabs in the tested specimens were subjected to bending that yielded eccentric compression in the joint. With an increase of the eccentricity the confining effect decreases correspondingly, hence, the ductility also decreases. The relation between ductility parameter and eccentricity is in inverse proportion. It allows getting a following expression for $\mu_{joint} = f(e)$, where μ_{joint} is the ductility parameter for element 4 of the joint (see Figure 1); $e = M / N$ is the eccentricity, changing the confining effect;

M is the maximum bending moment, acting on the slab;

N is the maximum axial force, acting on the column.

The limits for μ_{joint} are $\mu_{col} \leq \mu_{joint} \leq \mu_{conf}$, where μ_{col} is the column's ductility; μ_{conf} is the maximum value of μ_{col} due to maximum slab confining effect. As it follows from the previous research [7], $\mu_{conf} = 2\ \mu_{col}$.

To express the relation between μ_{joint} and the eccentricity e, following the experimental data, the relation was assumed to be linear (Figure 4). The joint ductility μ_{joint}, corresponding to a given eccentricity e_{joint}, can be obtained as

$$\mu_{joint} = \mu_{conf} - e_{joint}\ \ \mu_{col} / e_{unconf} \tag{1}$$

where e_{unconf} is the minimum eccentricity value, for which the confinement effect becomes negligible (when $e = 0$, the confining effect is maximum).

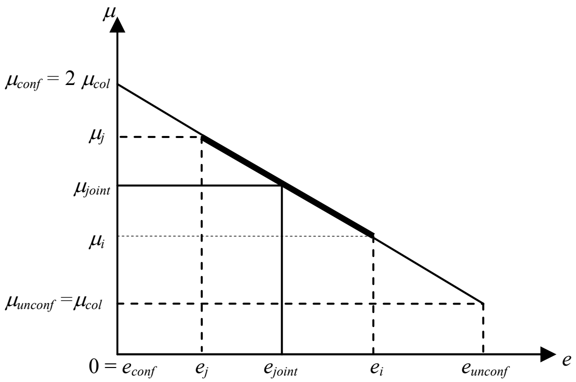

Figure 4: Ductility parameter μ_{joint} vs. eccentricity e (following [15]).

Using Figure 4 and the assumption that the relation between the ductility and the eccentricity is linear, the following proportion can be obtained:

$$\mu_{col} / e_{unconf} = (\mu_j - \mu_i)\ /\ (e_i - e_j) \tag{2}$$

To find the value of e_{unconf} the experimental data from Table 1 can be used:

$$e_{unconf} = \frac{\mu_{col}\left(e_i - e_j\right)}{\mu_j - \mu_i} = \mu_{col}\ \frac{(6.3-2.7)cm}{4.44-2.25} = 1.644\ \mu_{col}\ ,\ cm = \beta\ \mu_{col} \tag{3}$$

where β = 1.644 cm is an experimentally obtained parameter, taking into account the influence of the eccentricity.

Substitution of eqn. (3) into eqn. (1) yields:

$$\mu_{joint} = (\mu_{conf} - e_{jint} / \beta) \geq \mu_{col} \tag{4}$$

According to the experimental results [13], lateral strains in the slab direction, measured in the middle of the joint (ICSA-2), are about twice lower than those on the face of the column. Addition of ties in ICSA-4 decreases this difference up to 1.5 times. It is because additional confining effect is achieved by using ties in the joint. The ductility parameter in this case increases accordingly 2 / 1.5 = 1.33 times. Hence, the equation for calculating the ductility parameter for flat-slab column joints with additional ties can be given as follows:

$$\mu_{joint} = \gamma\,(\mu_{conf} - e_{joint} / \beta) \geq \mu_{col} \tag{5}$$

where γ = 1.33 is a coefficient, taking into account the ties' influence on ductility.

Figure 5 illustrates behaviour of ICSA-3 and ICSA-4 specimens with different steel ratios. The average joint lateral strains of both specimens were almost the same (about 2.25 10^{-3}) until the bearing capacity of ICSA-3 was achieved. Up to this limit the increase of the steel ratio almost twice does not yield any change in the joint's strains. However, the specimen with higher slab steel ratio demonstrated development of plastic deformations until 3.5 10^{-3}, corresponding to the bearing capacity of ICSA-4. It is because the slab reinforcement provides additional confining effect to the joint.

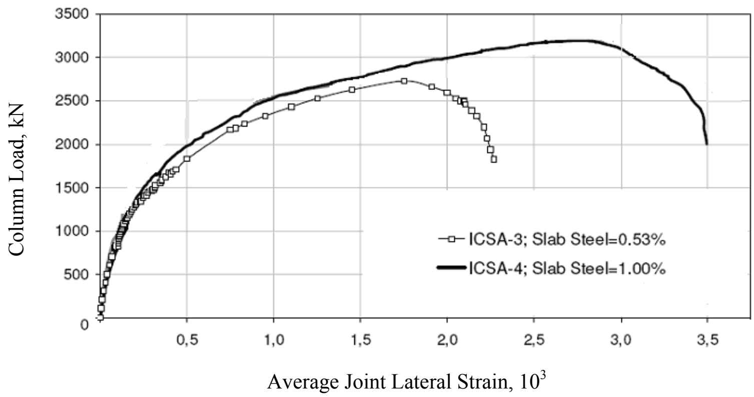

Figure 5: Effect of slab reinforcement on column-joint behaviour (following [15]).

Based on the above mentioned results, it can be concluded that the ductility parameter for ICSA-4 is about two times higher compared to that of ICSA-3. Hence, eqn. (5) can be updated as follows:

$$\mu_{joint} = \delta\gamma(\mu_{conf} - e_{joint} / \beta) \geq \mu_{col} \tag{6}$$

where δ = 2 is a coefficient, taking into account the slab steel ratio influence on the joint's ductility.

5 Conclusions

Current requirements to design of high performance structures form a basis for development of new approaches for materials and elements, which are able to resist a wide variety of external loads. This study was focused on complex experimental and theoretical investigation of column – flat slab joints ductility, which is one of the most important parameters for design of structures.

Preliminary attempts for calculation of two-layer RC beams' ductility resulted in theoretical background for an optimal design method, taking into account the stress-strain stage of such elements. A column – flat slab joint is a 3D element and its ductility in horizontal (slab directions) and vertical (column direction) is different. It is because the concrete, used in the elements, has different classes – the slab and the joint are made of NSC and the columns are from HSC.

In case of column – flat slab joints essential contribution to joint's ductility can be obtained due to the slab's confining effect. Effect of the ratio between the slab thickness and the column's section dimension on ductility is also significant. The slab steel ratio and the additional ties in the joint also have a significant influence on joints' ductility.

Equations for obtaining a quantitative value of the joint's ductility were developed. These equations consider the influence of all above mentioned factors (i.e. the ratio between the slab thickness and the column's section dimension; bending moment in the column – flat slab joint; slab steel ratio; and influence of additional ties).

Further research should be carried out in order to study the effect of fibre reinforcement in sensitive zones of HSC columns.

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