On detailing of reinforced-concrete frame structures for robustness and for earthquake resistance

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SUMMARY:
In recent years many efforts and research have been invested to satisfy the urgent need to achieve robust structures. The main reasons for these efforts are the failure and collapse of many structures due to events of terrorism in different parts of the world. The European Cooperation in Science and Technology (COST) Action TU0601 titled "Robustness of Structures" is a research network established with the main objectives to provide the basic framework, methods and strategies necessary to ensure a minimum level of robustness of structures. By satisfying this level of robustness, the structural systems are expected to be adequate and sufficient in relation to their function and exposure over their life time. This article summarizes the results from investigating the effect of varying reinforcement and detailing of beams and beam column joints in reinforced concrete frames on the structural functionality of the frame after a column removal.

Keywords: robustness of concrete structures, earthquake resistance, non-linear analysis, structural design codes

1. INTRODUCTION

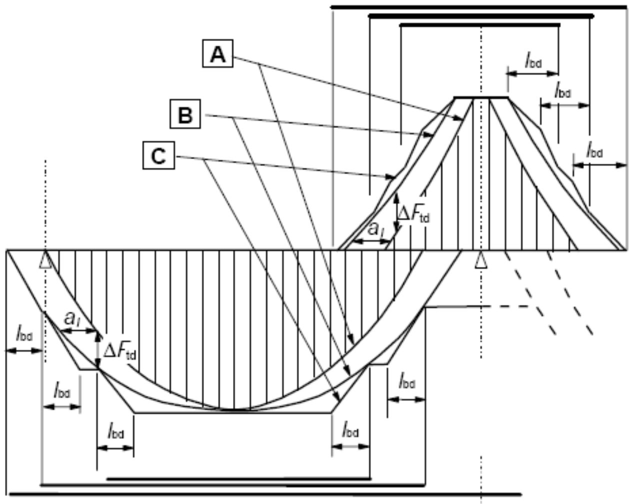
Robustness of structures became important in structural design, aiming for preventing disproportionate collapse as a consequence to initial damage and leading to collapse resistant structures. In this paper some accepted and common parameters in structural design are examined. Focus on the effects of varying reinforcement and detailing of reinforced concrete beams and frames on the structural functionality of the frame after a column removal as a result of an extreme event. By ensuring facilities for alternative load paths development and avoiding progressive collapse. Among these effects: curtailing the longitudinal flexural tension reinforcement along beams, redistribution of moments at beam column joints, increasing moments and reinforcement at spans and decreasing them at beam column joints, lap length in supporting regions with a view to facilitate reinforcement functionality in compression for usual cases and for full functionality in tension after support (column) removal, The use of closed links for shear reinforcement instead of bent-up bars and concrete confinement.

In addition examination is made against codes requirements which are valid for reinforced concrete structures design and for earthquake resistance. This study draws conclusions for complementary instructions and regulations in structural design codes for reinforcement details corresponding to robustness and earthquake resistance of structures.

2. LONGITUDINAL FLEXURAL REINFORCEMENT DESIGN ALONG BEAMS

2.1. Longitudinal Flexural Tension Reinforcement

Large effort is invested in designing curtailing of the longitudinal flexural tension reinforcement along beams according to design codes recommendations, see Figure 1 from EC2 for instance, following-up and concerning to resist the acting tensile force envelope.



[A] - Envelope of $M_{Ed}/z + N_{Ed}$ [B] - acting tensile force F_s [C] - resisting tensile force F_{Rs}

Figure 9.2: Illustration of the curtailment of longitudinal reinforcement, taking into account the effect of inclined cracks and the resistance of reinforcement within anchorage lengths

Figure1. Curtailment of longitudinal reinforcement Euro code 2 [EC2, 2004]

In Figures 2 and 3 given two examples for reinforcement detailing along the beam and for resisting the acting tensile force envelope accordingly. Figure 2 demonstrates curtailment of longitudinal reinforcement. Figure 3 in contrast, all required reinforcement area at midspan continues as straight bars with sufficient anchorage length at supports.

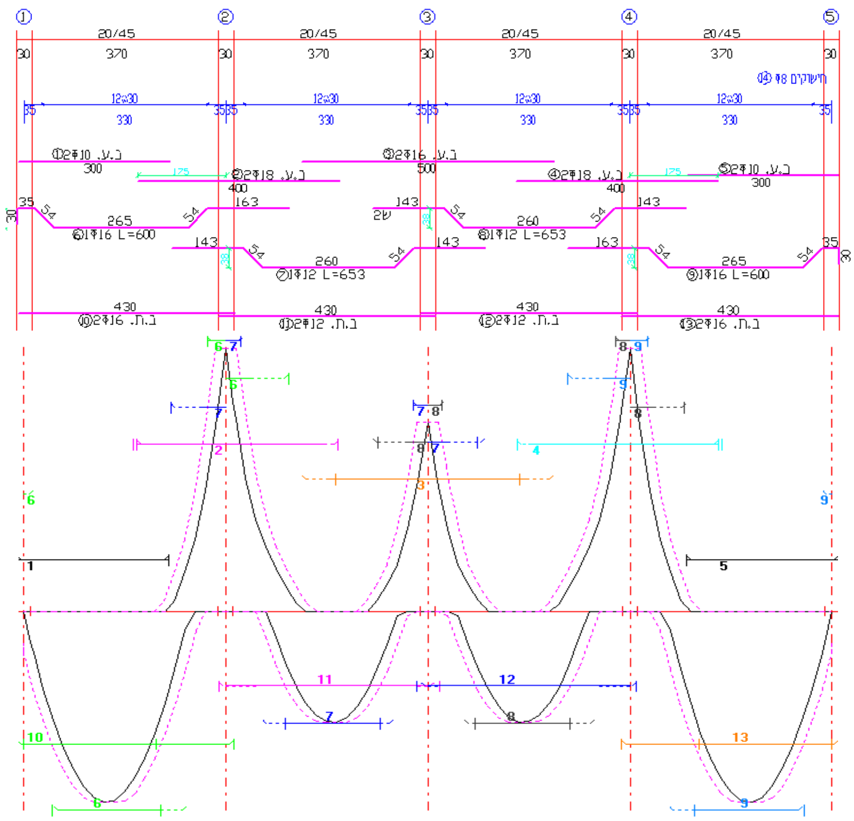


Figure2. Example for beam reinforcement detailing with curtailment

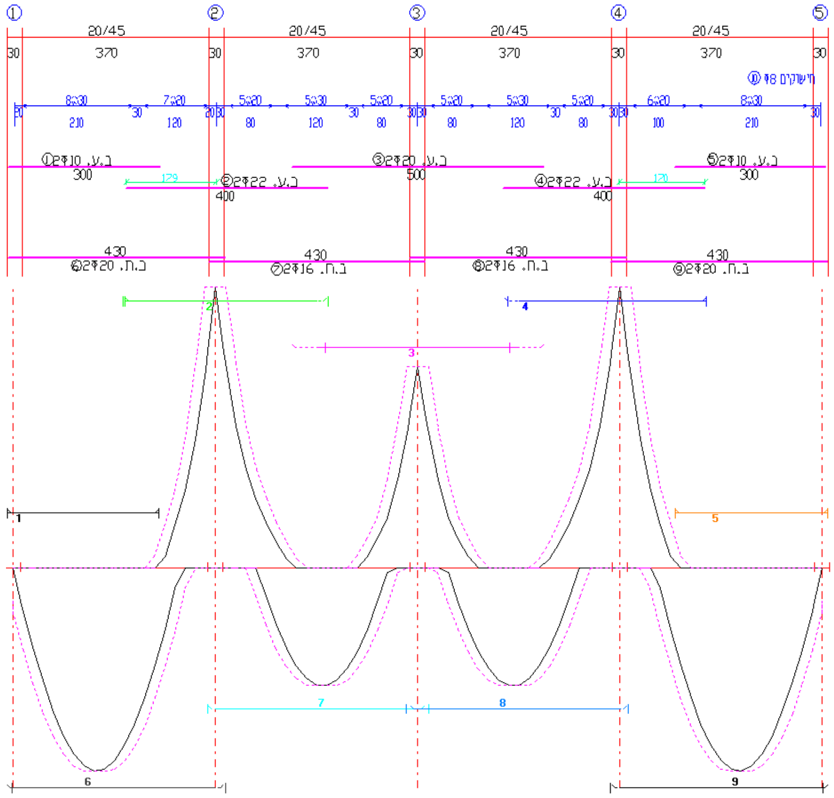


Figure3. Example for beam reinforcement detailing without curtailment

Apparently this investment in longitudinal reinforcement curtailment along beams according to design codes recommendations is unnecessary and even essential to avoid it In order to increase the robustness of structures and to prevent progressive collapse. For example, in case of loss of internal support (column removal in the building as a result of an unusual event) in the two examples given in Figures 2 and 3, resulting in doubling the length of the functioning span, and to increasing demand for bottom reinforcement amount at span.

When the full amount of reinforcement required at midspan is continued to the supports (straight bars) with sufficient anchorage length at supports, the reinforcement amount functioning in tension as bottom reinforcement at intermediate support after support absence will be significantly greater. For illustration see Figure 3 versus Figure 2.

This can increase the robustness of the structure considerably. For instance, in case of sufficient anchoring at supports, the full amount of reinforcement required at midspan compared to the case of only half of the amount of reinforcement required at midspan is anchored at supports and the second half is stopped because of curtailment, would double the robustness and the flexural resistance of the beam at a ratio of two at least.

Figure 4 illustrates the requirements for longitudinal flexural tension reinforcement detailing along the beam and for resisting the tensile force envelope, after an interior support removal. In addition the demand for longitudinal flexural compression reinforcement along the beam is obvious and indicated; compression bars were required and detailed. Even additional special bars in compression were required, more than the full amount which was full anchored from neighbouring spans. This compression reinforcement area can be downloaded via redistribution of moments at supports as is treated later in this article.

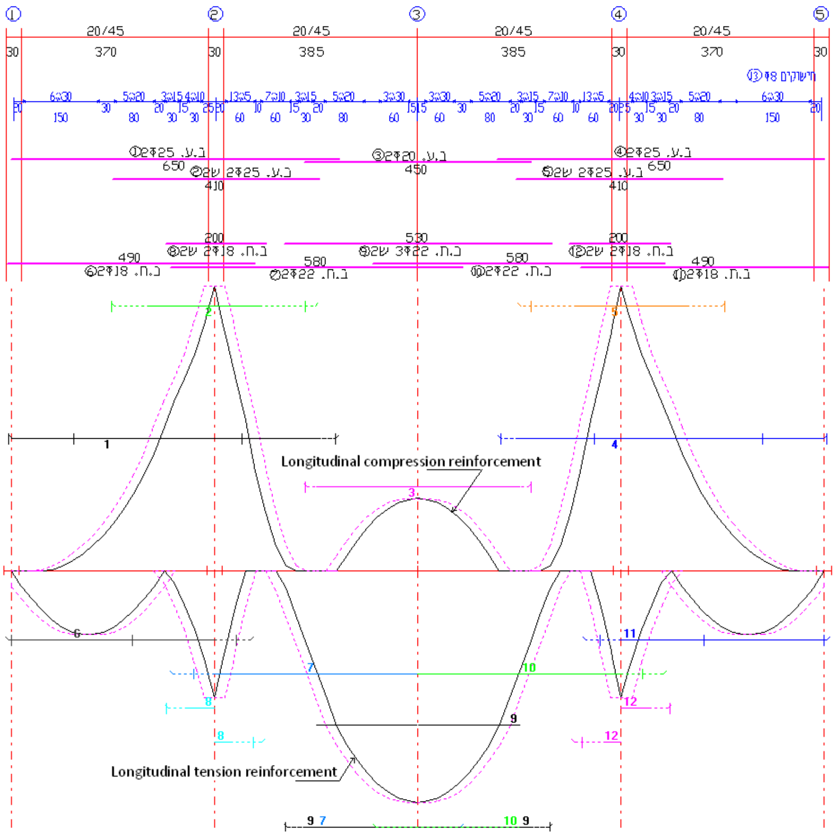


Figure4. Example for beam reinforcement detailing after an interior support removal

2.2. Longitudinal Flexural Compression Reinforcement

Longitudinal flexural compression reinforcement is essential for increasing the robustness and the flexural resistance, as indicated in the previous section, in the event of a serious incident and support elimination. The contribution of compression reinforcement to increase section capacity in flexure is known and proven. So the goal is to enable reinforcement given along the beam, for any purpose it is calculated and intended, transmitting compressive forces, in any event leading it to function as compression reinforcement, by ensuring reinforcement continuity, through supplying adequate lap length. Reinforcement bars given under minimal requirements included in this category. In addition compression reinforcement has an important role in the development of alternative static schemes after an exceptional event.

It should also be noted that section compressive reinforcement reduces the compression transmitted to the concrete and reduces the developing strains in concrete as a result, and therefore contributing positively by increasing the essential ductility at critical areas. The concrete confinement Issue and the contribution of compression reinforcement are detailed below in section 4.

2.3. Anchorage of Bottom Reinforcement at Intermediate Supports

The anchorage lengths of bottom reinforcement at intermediate supports recommended by design codes, see Figure 5 from EC2 for instance, are insufficient and do not contribute to the robustness of structures. For small financial investment of not significant additional anchorage length it is possible to increase and raise the reinforced concrete beam robustness level and as a result the structural robustness significantly.

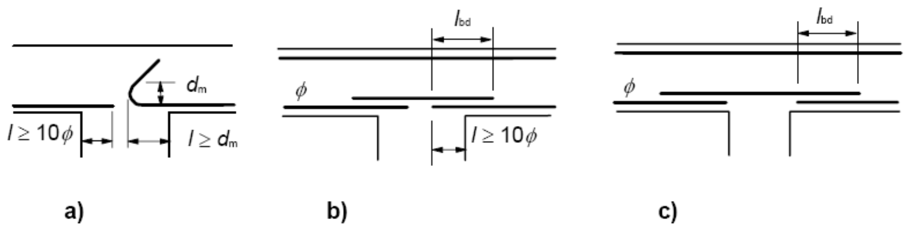


Figure 9.4: Anchorage at intermediate supports

Figure5. Anchorage at intermediate supports Euro code 2 [EC2, 2004]

Additional anchorage length as described provides continuity to reinforcement and the ability for transmission of tension forces developing in case of interior support removal, see Figure 4, and helps in the development of alternative load paths for load transfer in case of an extreme event. The intention is to provide full lap length of bottom reinforcement at intermediate supports for the whole amount of reinforcement required at midspan, giving partial answer for the maximum positive moment developing at bottom supporting regions.

In addition it should be noted that full lap lengths of bottom reinforcement at intermediate supports enable reinforcement functionality in compression and transmitting of part of compression forces at critical sections designed for plastic behaviour, lead to concrete strains reduction and to increasing section ductility as a result.

2.4. Redistribution of Moments at Beam Column Joints

Redistribution of moments along the beam according to the trend of decreasing the moments at interior beam column joints and increasing moments and reinforcement at spans is recommended. This can contribute, in addition, to earthquake resistance by following and matching strong column – weak beam concept and development of plastic hinges in beams. Furthermore it is recommended to keep constant the whole amount of reinforcement required in the critical section at midspan along the beam span. In other words it is recommended to use straight reinforcement bars adequately anchored at supports.

This step in conjunction with the previous recommended step for full lap length of bottom reinforcement at intermediate supports increases the amount of bottom reinforcement supplying the demand for the maximum positive moment developing at bottom supporting region after support removal.

3. SHEAR REINFORCEMENT DESIGN

Design codes requirements for shear reinforcement design must take into account the issue of ensuring robustness for structures and reducing the risk of chain reaction of failures and preventing progressive collapse in an explicit or implicit way. Apparently this is not implemented by Current design codes. If we examine the provisions of EC2 for instance:

“9.2.2 Shear reinforcement
(1) The shear reinforcement should form an angle α of between 45° and 90° to the longitudinal
axis of the structural element.
(2) The shear reinforcement may consist of a combination of:
- links enclosing the longitudinal tension reinforcement and the compression zone (see
Figure 9.5);
- bent-up bars;”

This recommendation gives the closed links and bent-up bars equal status!

Bent-up bars recommendation will always be at the expense of closed links and would eliminate of their many advantages, even in the limiting concrete crack and in the field of enhancing concrete behaviour, stress-strain relationship, confinement and increasing ductility.

Usually the regions with maximum shear stresses are the regions near supports, where the maximum required shear reinforcement, that is where links densification required to provide a solution for shear. On the other hand additional advantage is obtained from links densification that is providing concrete confinement and increasing concrete ductility at the critical regions designated for the development of plastic hinges in beams according to the principle of weak beam – strong column, contributing to increased and improved earthquake resistance and robustness of structures.

In summary the solution for shear reinforcement along the beam and especially the supporting regions using only dense vertical closed links and eliminating the use of bent-up bars from spans, can simplify the task of performance and of calculation, can improve the ratio of stress - strain in concrete due to confinement. It also can contribute significantly to restrain the crack in concrete.

4. CONCRETE CONFINEMENT

Inherent ductility and continuity of the structure allow the development of alternative static schemes for load redistribution and transfer after a catastrophic event occurring and increase structural robustness and earthquake resistance.

Improving ductility of reinforced concrete elements is possible through two main factors: first reducing the pressure transmitted to the concrete, thereby reducing the concrete strains. This can be achieved through the longitudinal flexural compression reinforcement as explained in section 2.2 above. The second factor is through the confinement of concrete and improving the ratio of stress - strain in concrete raising and upgrading concrete constitutive relationship. Confinement can be achieved by adequately closed links.

Consideration for confinement of concrete by closed links and longitudinal bars can be taken into account according to the model and the expressions described in EuroCode2, see Figure 6 from EC2.

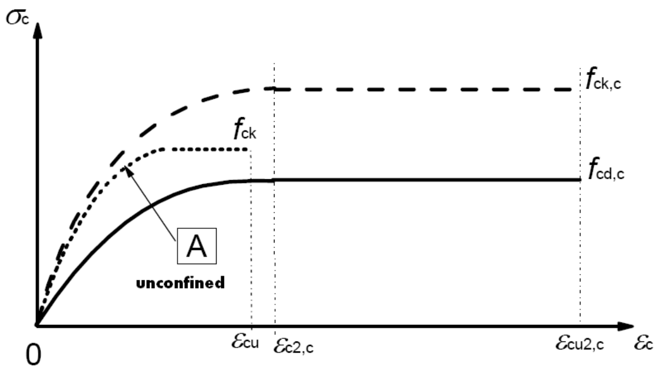


Figure6. Stress-strain relationship for confined concrete Euro code 2 [EC2, 2004]

In conclusion increasing the potential strength and strain in concrete under the influence of confinement can contribute greatly to the robustness of reinforced concrete structures. Expressing the effect of increasing in the potential concrete strains and strength is possible through non - linear analysis of the structure.

5. DIMENSIONING OF BEAMS, COLUMNS AND BEAM COLUMN JOINTS

Common design philosophy for reducing the risk of chain reaction of failures, preventing progressive collapse and increasing robustness of structures is preparing alternate paths for transferring the load in the event of a catastrophic event in the early stages of structural design. One principle is bridging over areas with high probability of failure, for example for the failure of a supporting column on the ground floor.

On the ground floor there is a higher probability of extreme events and failures. Increasing the dimensions of the beams at first floor slab level and increasing their rigidity over than necessary by other design requirements will allow formation of bridging operation over zones that might be injured on the ground floor such as eliminating supporting columns.

In the example described in Figure 7, a reasonable increase of dimensions of the beam at first floor slab level 300/650 mm relative to the dimensions of the beams in the upper floors levels 200/450 mm can successfully bridge over the injured zone in case of interior support eliminating at ground floor, and maintains the possibility of partially supporting action along the support axis on the upper floors activating the main massive top longitudinal reinforcement given at supports regions and utilizing the non – linear range of behaviour.

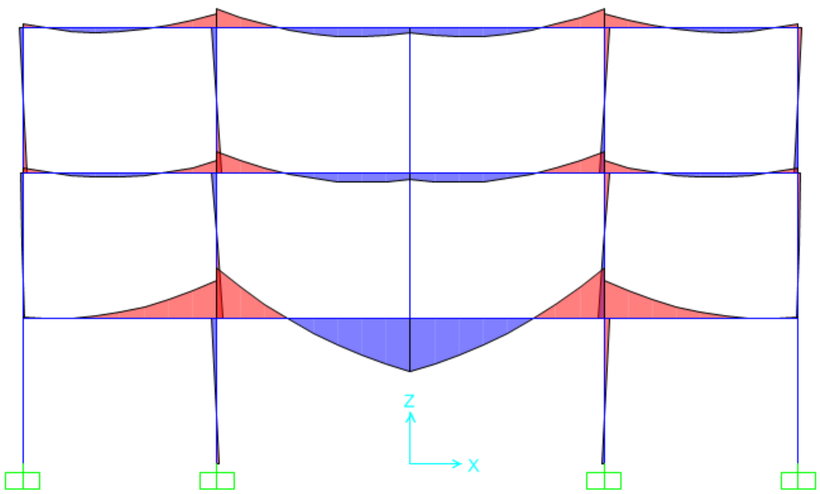


Figure7. Bridging over injured zone, interior support elimination, by increasing beam dimensions

For the development of plastic hinges in beams, maintaining the strong column–weak beam concept, leads to increase the dimensions of the columns on the first floor. On the other hand this increase of columns dimensions on the ground floor reduces the probability of failure due to increasing stiffness of the columns and increases the robustness of structure.

6. CONCLUSIONS

Some accepted and common parameters in structural design were examined from the perspective of robustness of structures, enabling people safety and avoiding human life injury in the event of abnormal loads and preventing progressive collapse. The following conclusions regarding reinforcement and detailing of reinforced concrete beams and frames were drawn.

- Design codes recommendations for curtailing of the longitudinal flexural tension reinforcement along beams should be cancelled. Instead, the full amount of reinforcement required at midspan should be continued to the supports keeping reinforcement continuity by means of full lapped bars.
- The requirements for anchorage of bottom reinforcement at intermediate supports should be

replaced by full lap length, for facilitating reinforcement functionality in compression for usual cases and for full functionality in tension in case of support removal, providing alternative load paths and enabling redistribution of forces.

- Full lapped bars of bottom reinforcement at intermediate supports, facilitating reinforcement functionality in compression, as mentioned above, decreases concrete stresses and strains in compression and increases the ductility in these regions.
- Emphasizing the preference for closed links to receive shear stresses along beams, especially in regions of maximum shear forces near supports, instead of bent-up bars, due to the prominent advantages in increasing confinement for concrete, enhancement of concrete constitutive relationship and crack limitation along the beams.
- Alternate load paths for transferring and redistributing the loads in case of extreme event should be prepared and ensured in the early stages of the structural design, for instance increasing the dimensions of the beams at first floor slab level to allow formation of bridging operation over zones with high probability of failure on the ground floor, such as eliminating of supporting columns.

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