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Comparison on Code Methods for Flexure and Shear Design of Reinforced Concrete Beams and Proposal for a Common Design Code

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Abstract: **The presented paper gives a comparison in the design of reinforced concrete beams between the Chinese code GB 50010, the European code Eurocode 2 and the American code ACI 318. From a concrete structure composed of a slab and several beams, the design of rebars of reinforced concrete beams is made according to the three design codes. The comparison is based on the calculations of the ratios between the different values of areas of reinforcement. In this research, we determine which code is the most conservative by using the same value for the steel yield strength. In flexure design, the results of rebar areas are approximately similar. It appears Eurocode 2 is the most conservative code. The codes are mainly equivalent and the differences between the codes are about 10% or 20%. In shear design, we observe more discrepancies than in flexure design but the stirrups ratios of two compared codes stay in a range globally between 1 and 2. ACI 318 is, in most cases, the most conservative code. Then with all the calculated ratios, a relation is given between the codes by the utilization of trend-lines which describe the distribution of all the calculated data. This paper is presented as follows. First, we deal with the presentation of the project and the calculation method. Then, we show the results of the comparison. Finally, a proposal on a common, international design code is given.**

Keywords: **comparison, design code, flexure, shear, reinforced concrete beams.**

1. INTRODUCTION

Concrete structures are one of the most common structures in the world. Engineers follow the design code rules where a structure is built. Each country follows its own design code, except for the European Union which is a group which has the common code Eurocodes. However there is no international code which stands for the reference in the world. Thus, if we consider a given structure, the difference between the codes will lead to different values for the steel areas of reinforcement. The present deals with a comparison of the concrete structures design codes of three areas of the world: the People's Republic of China, the European Union and the United States of America. What can be expected from such a comparison? We may reasonably expect there are not so many differences between the codes but we need to check by a scientific comparison based on givens and results. Then, this research shows a link between the codes and also propose a standardization of design in the world.

All the calculations and results of this research come from the reference [1]. An appendix for notations and abbreviations is given at the end of this paper.

2. EXPLANATION OF THE COMPARISON

2.1 DESCRIPTION:

Comparing design codes is not an easy task. But two kinds of comparison are possible. First, we can make a comparison about the theory and the formulas. In this case, the comparison deals with the "ways of thinking" of the design codes. This comparison is based on probabilistic and subjective considerations which are very complicated. Each code follow its own rules which are specific particularly because of the laws in the countries or the customs in the construction sector. Secondly, starting from givens we can obtain some results and, then, comparing the design codes is possible. The code is considered as a “black box”. We introduce the inputs and we get the outputs which can be analyzed for the comparison.

The chosen comparison of the present paper deals with the second kind of comparison. The “black box” with givens and results. We have utilized two assumptions. The assumption 1 is the studied structure is the same for the three codes. This assumption is obvious because in order to have a fair comparison, it is normal to consider the same structure. Besides the conditions of utilization of the structure are the same. Our studied structure is a shopping center which is also called stores and shops in the design codes. The assumption 2 is the use of the same value of yield strength for the reinforcement which is 400 MPa.

2.2 PRESENTATION OF THE STRUCTURE:

The structure is a floor of a shopping center. It is a one-way slab supported by beams. The beams have a T-shaped section. So the calculations are lead according to the calculations of a T-beam. The environmental conditions are those of an indoor normal environment which is the wording used in the Chinese code[3]. This is the most favorable condition for a structure. The European code[5] and the American code[7] have their own wording.

The two basic dimensions are the span of the beam l_0 and the center to center spacing between two beams s_b. The span of the beam is the length of the slab and the center to center spacing between two beams is the width of the slab. In this paper, in order to simplify the writing, the center-to-center spacing between beams is just called spacing between beams. The Fig. 1 shows the slab and the beams of the floor.

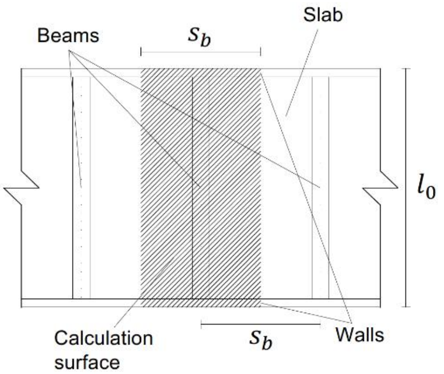

Fig. 1 Slab and beams of the floor

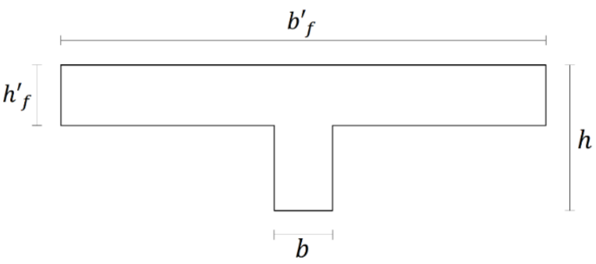

Fig. 2 T-beam cross-section

The beam is a simply supported beam. For flexure design, the control section is the same for the three codes[3] [5] [7]: it is the mid-span section of the beam. For shear design, the control section is not the same for the three codes. For the Chinese code[3], the control section for shear force is located on the support of the beam. For the European code[5] and the American code[7], the shear control section is located at a distance d from the support in which d is the effective depth of the beam. The other dimensions of the beam are the depth of the beam h, the width of the web b, and the depth of the flange h'_f. We also need to define the effective width of the flange b'_f. The Fig. 2 shows the cross-section of the T-beam.

The dimensions of the section are determined by the utilization of assumptions based on usual ratios used by engineers in order to have efficient proportions for the beams. In this paper these ratios allow obtaining the same dimensions of the beam which can be put into the three codes. The depth of the beam is $h = l_0/14$, the width of the web is $b = h/3$, and the depth of the flange is $h'_f = max(s_b/26\,; 0.06\,m)$. This choice for the depth of flange, which represents the slab thickness, gives a realistic range for h'_f between 6 cm and about 15 cm according to the dimensions cases. The determination of the effective width of flange b'_f depends on the three codes.

The beam is a simply supported beam which is uniformly loaded. The two considered loads are the dead load (self-weight and superimposed dead load) and the live load.

In this study, we use a C25 grade concrete. The longitudinal reinforcing bars for the flexure design are only located in the tension zone (singly reinforced beam) and we use only vertical stirrups for shear reinforcement. For the value of the yield strength of the reinforcement, we have chosen 400 MPa which respects the rules of the three codes[3] [5] [7].

2.3 DIMENSION DATA:

In a comparison, the number of data is very important. The more we have data, the more accurate is the comparison. Our study is composed of 44 different dimensions cases for the span of the beam and the spacing between beams. The following dimensions for the span length and the spacing between beams correspond to usual values in building engineering. The value of the span length is between 3 meters and 8 meters. The chosen dimensions for the spacing between beams is between 0.75 meter and 4 meters. These choices represent a usual beams setting for the one-way slab assumption. The ratio span/spacing between beams is between 2 and 4.

2.4 OBJECTIVES:

The objective of this research is to give an estimation of the areas of the reinforcing bars. From a given concrete structure, we calculate the rebar areas. The paper starts with an evaluation of the rebar areas obtained after calculations and design in the different codes. Then we can make a ratio between the results of the different codes and try to find a relation between the ratios of the different codes. We can obtain a great number of data by varying the basic dimensions of the concrete structure. In other words, we make a variation in the value of the span of the beam and the center-to-center spacing between beams as we will deal with in the following parts.

3. COMPARISON OF THE THREE CODES

3.1 COMPARISON BETWEEN CHINESE CODE GB 50010 AND EUROPEAN CODE EUROCODE 2:

Fig. 3 and Fig. 4 show the flexure comparison ratio $A_{s,EC2} / A_{s,GB}$ in small scale and in large scale respectively. Fig. 5 shows the shear comparison ratio $(A_{sv} / s)_{EC2} /(A_{sv} / s)_{GB}$ and its trend-line.

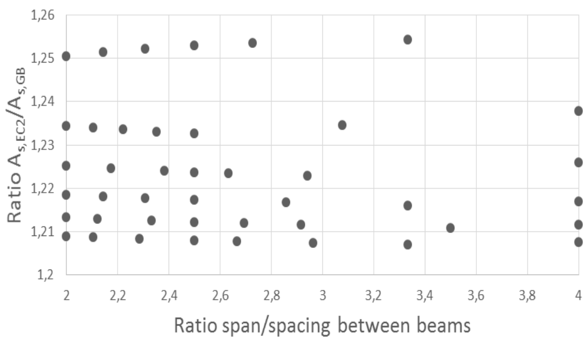

Fig. 3 Data in small scale - Flexure - GB-EC2

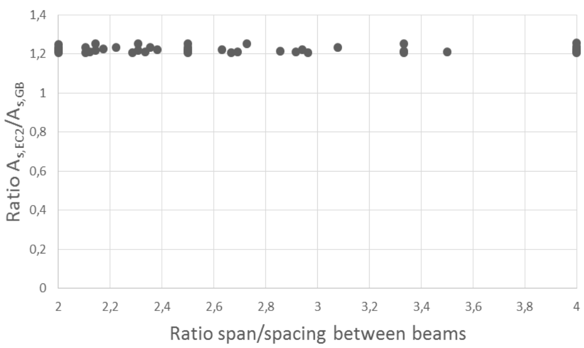

Fig. 4 Data in large scale - Flexure - GB-EC2

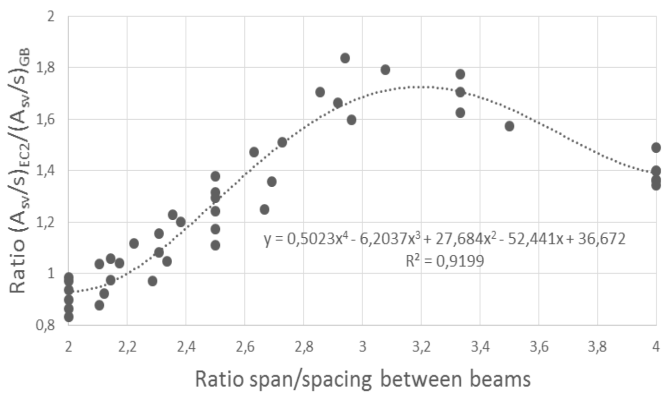

Fig. 5 Data and trend-line - Shear - GB-EC2

3.2 COMPARISON BETWEEN CHINESE CODE GB 50010 AND AMERICAN CODE ACI 318

Fig. 6 and Fig. 7 show the flexure comparison ratio $A_{s,ACI} / A_{s,GB}$ in small scale and in large scale respectively. Fig. 8 shows the shear comparison ratio $(A_{sv} / s)_{ACI} /(A_{sv} / s)_{GB}$ and its trend-line.

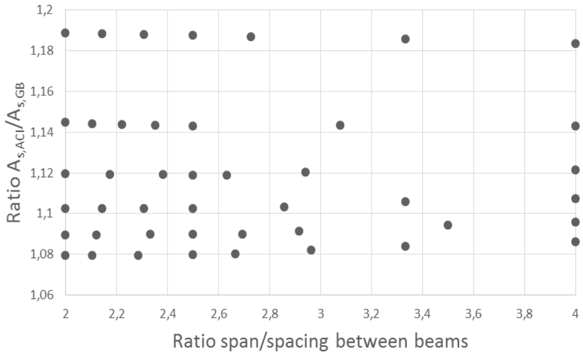

Fig. 6 Data in small scale - Flexure - GB-ACI

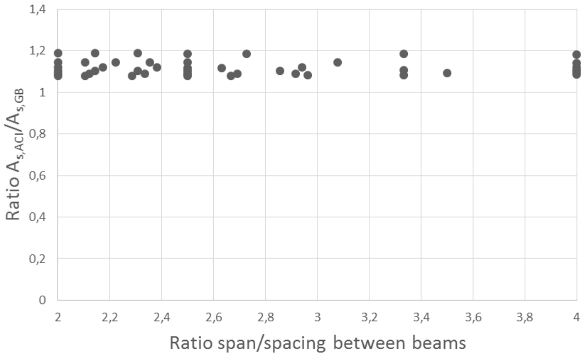

Fig. 7 Data in large scale - Flexure - GB-ACI

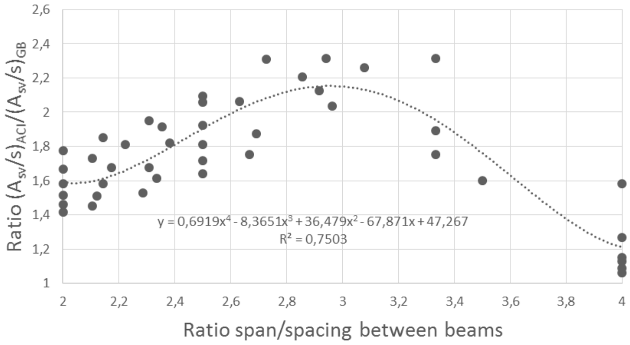

Fig. 8 Data and trend-line - Shear - GB-ACI

3.3 COMPARISON BETWEEN EUROPEAN CODE EUROCODE 2 AND AMERICAN CODE ACI 318

Fig. 9 and Fig. 10 show the flexure comparison ratio $A_{s,EC2} / A_{s,ACI}$ in small scale and in large scale respectively. Fig. 11 shows the shear comparison ratio $(A_{sv} / s)_{ACI} / (A_{sv} / s)_{EC2}$ and its trend-line.

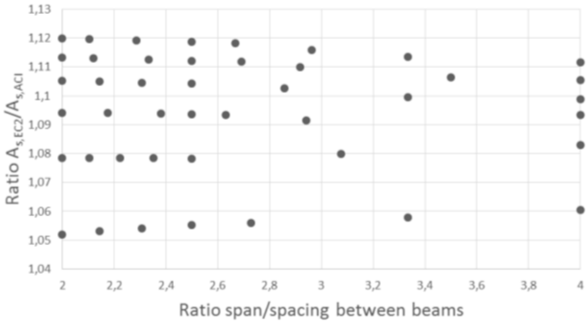

Fig. 9 Data in small scale - Flexure - EC2-ACI

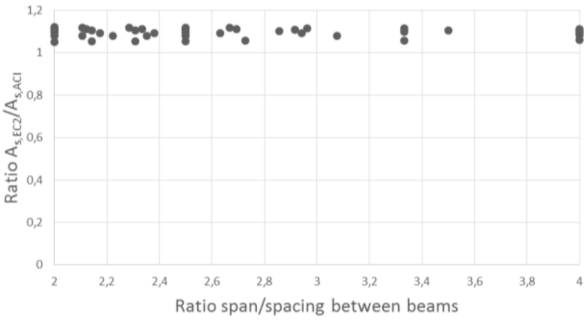

Fig. 10 Data in large scale - Flexure - EC2-ACI

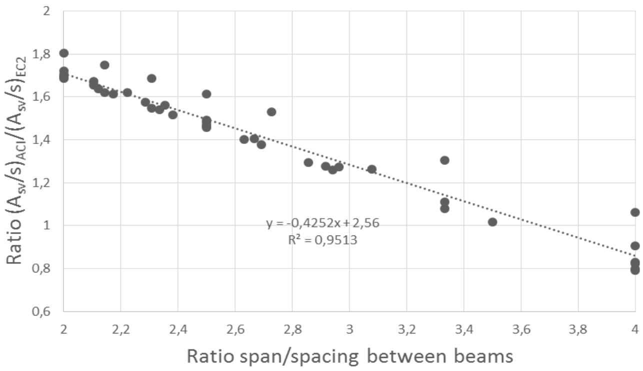

Fig. 11 Data and trend-line - Shear - EC2-ACI

3.4 SUMMARY OF THE RESULTS:

For flexure design, Eurocode 2 is the most conservative code and GB 50010 the least conservative. ACI 318 is between the both. Nevertheless the results between the three design codes seem to be equivalent. For example, in the comparison between Eurocode 2 and GB 50010, we only need to multiply the rebar areas of the Chinese code by 1.22 in average in order to obtain the rebar areas of the European code. Besides, in the comparison between Eurocode 2 and ACI 318, the European rebar areas are only 1.09 times higher than the American ones. Another interesting information is about the calculated between the rebar areas of two codes. The relation between can be considered as a constant. In fact, in each dimension case we have studied, the ratio between the rebar areas of two compared codes are very close to the mean value because the coefficient of variation of the results is very small.

For shear design, ACI 318 is globally more conservative than Eurocode 2 and GB 50010. And Eurocode 2 is more conservative than GB 50010, except in the case where the span/spacing between beam ratios have a value between 2 and 2.2. We can easily show the differences between the codes with the graphs of the trend-lines. In fact, by varying the span/spacing between beams ratios, the differences are reduced and, in some cases, inverted. For the comparison between GB 50010 and Eurocode 2, the calculated ratios are located in a range from 0.83 to 1.84. So for a ratio between 0.83 and 1.84, which corresponds to a span/spacing between beams between 2 and 2.2, GB 50010 is more conservative than Eurocode 2. But, when the span/spacing between beams ratio overtakes 2.2, Eurocode 2 becomes more conservative. For the comparison between GB 50010 and ACI 318, the range of the calculated ratios is located from 1.06 to 2.32. And in the comparison between Eurocode 2 and ACI 318, the range is located from 0.79 to 1.80. In this case, when the span/spacing between beams ratios overtakes the value 3.7, Eurocode 2 is more conservative than ACI 318. But, except in this particular range, ACI 318 is more conservative than Eurocode 2.

3.5 COMMENTS OF THE RESULTS:

For the three comparisons, we can notice some general statements about the differences between the codes and the way they differ.

In flexure design, the results are quite similar which is not very surprising. Besides, the large scale graphs underscore the fact that the results of a comparison are near a mean value for all the range of the span/spacing between beams ratios.

In shear design, we observe some discrepancies between the codes. The graphs are very useful to characterize these differences. In the comparisons GB 50010/Eurocode 2 and GB 50010/ACI 318, span/spacing between beams approximately between 2 and 3, the ratios of areas of reinforcement increase. Then, for a ratio span/spacing between beams approximately between 3 and 4, the stirrups areas ratios decrease. This curve peak is due to the fact that the calculated Chinese stirrups areas have reached the minimal value at about the value 3 for the span/spacing between beams ratios. And in the interval between 3 and 4 in the horizontal axis, the European and American stirrups areas continue to decrease because the more we increase the span/spacing between beams ratio, the less the structure is subjected to shear. This means a reduction of the calculated stirrups areas. At the same time, the Chinese stirrups areas have reached their minimal value. Thus, at the right side of the graphs, the gap between GB 50010 and Eurocode 2 and the one between GB 50010 and ACI 318 are reduced. In the Eurocode 2/ACI 318 comparison, the calculated stirrups areas never reach their minimal values, therefore we do not observe any inversion of the curves.

3.6 UTILIZATION OF THE RESULTS:

In flexure design, we have plotted the calculated ratios in the vertical axis and the span/spacing between beams ratios in the horizontal axis. And we show the results on two kinds of graphs where we change the scale of the vertical axis: one in a small scale and one in a large scale. The small scale graphs are useful to show the fact we cannot find any trend-line. Then, the large scale graphs shows the results are close to a same value which is also underscores by a low coefficient of variation of the calculated ratios. Thus, in flexure design, the equivalence way between the codes is the mean of the values.

In shear design, for the three comparisons, the results of ratios are not close to the mean value. But, we have found that the link between the codes can be expressed by the equation of the trend-line of the results. In the vertical axis, there are the calculated ratios and, in the horizontal axis, there are the span to spacing between beams ratios. This trend-line is obtained with the software Excel and has a coefficient of determination R^2 as close as possible to 1.

The trend-lines are utilized for the case of shear design. The vertical axis is the calculated ratio between the stirrups areas of the two compared codes and the horizontal axis is the ratio span/spacing between codes. For the ratio on the horizontal axis, the values are between 2 and 4 because they are the dimension cases we have studied. These graphs represent a kind of "equivalence curve" because they are a link between two design codes. From a given ratio the ratio span/spacing between beams read on the vertical axis, we can get the calculated ratio between two codes in the vertical axis. Then, from a given value of area of reinforcement, we only have to make a multiplication in order to get the corresponding value of the other code. The Tables 1, 2 and 3 give the equivalence between the design codes.

Table 1 Equivalence table between GB 50010 and Eurocode 2

Comparison	Design and ratio	Equivalence ratio
Comparison GB 50010 - Eurocode 2	Flexure - Ratio $A_{s,EC2}/A_{s,GB}$	1.2242
	Shear - Ratio $(A_{sv}/s)_{EC2}/(A_{sv}/s)_{GB}$	$0.5023x^4 - 6.2037x^3 + 27.684x^2 - 52.441x + 36.672$ (x = span/spacing between beams)

Table 2 Equivalence table between GB 50010 and ACI 318

Comparison	Design and ratio	Equivalence ratio
Comparison GB 50010 - ACI 318	Flexure - Ratio $A_{s,ACI}/A_{s,GB}$	1.1196
	Shear - Ratio $(A_{sv}/s)_{ACI}$ / $(A_{sv}/s)_{GB}$	$0.6919x^4 - 8.3651x^3 + 36.479x^2 - 67.871x + 47.267$ (x = span/spacing between beams)

Table 3 Equivalence table between Eurocode 2 and ACI 318

Comparison	Design and ratio	Equivalence ratio
Comparison Eurocode 2 - ACI 318	Flexure - Ratio $A_{s,EC2}/A_{s,ACI}$	1.0941
	Shear - Ratio $(A_{sv}/s)_{ACI}/(A_{sv}/s)_{EC2}$	$-0.4252x + 2.56$ (x = span/spacing between beams)

The purpose of the use of the three previous tables is about giving direct equivalences between the codes. We can show it with an example. This example comes from the comparison between Eurocode 2 and GB 50010 in shear design and corresponds to a case where the span/spacing between beams is equal to 2.5. We start from the shear reinforcement value $(A_{sv}/s)_{GB}$ equal to 100 mm²/m. This value has been calculated according to the Chinese code GB 50010. However we want to obtain the value which would have been calculated according to the European code Eurocode 2. According to Table 1, the equivalence function is $f(x) = 0.5023x^4 - 6.2037x^3 + 27.684x^2 - 52.441x + 36.672$ with x = span/spacing between beams. And, in this example, x is equal to 2.5. So the polynomial function is $f(2.5) = 0.5023 \cdot 2.5^4 - 6.2037 \cdot 2.5^3 + 27.684 \cdot 2.5^2 - 52.441 \cdot 2.5 + 36.672 = 19.6211 - 96.9328 + 173.025 - 131.1025 + 36.672 = 1.283$. We just need to multiply this result by the initial value of $(A_{sv}/s)_{GB}$ and, then, we can obtain the value of the European code $(A_{sv}/s)_{EC2}$. Finally, we obtain $(A_{sv}/s)_{EC2} = (A_{sv}/s)_{GB} \cdot 1.283 = 100 \cdot 1.283 = 128.3\ mm^2/m$.

4. PROPOSAL OF A COMMON CODE

4.1 REASONS FOR THE CREATION OF A UNIVERSAL CODE:

Universalism is a highly broadcast idea in every sectors of our lives not only in science. The second part of the 20th century and especially the 21st century have developed these kinds of idea. Globalization leads the world to a progressive universalism. However, the design codes still remain a national question, or a continental question for the European Union. What would be the objectives of creating a universal code? In our globalized world, many construction projects are led by a foreign firm for a given country. For example, a Chinese company has a contract with a member of the European Union and has to build a structure in this country. It means the Chinese firm has to follow the rules of Eurocodes. This company is familiar with the Chinese code but not particularly familiar with Eurocodes. This inconveniency can create misunderstanding or, at least, a waste of time and money. Therefore, a universal code makes these kinds of situations more convenient for the firms which build in a foreign country. These sorts of situations are now very frequent, particularly in the developing country where the construction sector has a huge activity.

4.2 COMMON CODE BUT SPECIFIC COEFFICIENT FOR EACH COUNTRY:

The idea of a universal code has many advantages, especially for simplifying all the relations concerning designing in a foreign country. But which code should be taken as a reference? We consider the case where all the countries have chosen the same code to follow. We can consider this code as the virtual chosen code. In this code, all the countries make the same calculations for designing a structure. For example, in the case of a concrete structure as we deal with previously in this paper, designers of all the countries find the same areas of reinforcement for the reinforcing bars. But the countries do not necessarily want to obtain different results from their previous design code. For example, engineers of a country judge the universal code too conservative. They agree with the idea of utilizing the same code but they want to keep the same level of safety for the structures of their countries. That is why the idea of a “common code” is more suitable than a “unique code”. The use of a common code allows convenience for designing abroad but keep the requirements of each country.

4.3 WAY TO BUILD THIS COMMON CODE:

How to build this common design code? The existing case of the European Union is very interesting. From the beginning of the nineties, the members of the European Union have developed the same rules for designing structures in the territory of the European Union. A French firm which builds a structure in France follows the same rules as a German firm which builds a structure in Germany. Nevertheless, the countries have kept their requirements. Each country has a “National Annex” in which specific values are used. The Eurocodes give recommended values but the National Annexes give specific values which can be similar or different from the Eurocodes recommended values. Of course, the values of the National Annexes are not totally different from recommended ones but they express a certain difference of consideration towards designing for the countries. For example, the live loads taken into account for the calculations have recommended values but also specific values written in the National Annexes. Then, each country can abide by its own criteria about their degree of safety.

Utilizing different coefficients from the beginning of a design means the intermediary results are not the same. This can be a source of misunderstanding between two National Annexes for a firm which has to use another National Annex. This inconveniency leads a firm from a given country, which builds in another European country, to use the National Annex of the country where the structure will be built. In fact, this inconveniency is not a major inconveniency but the process of design may be accurately improved. According to the results shown in this paper, we can give another way to comply with the specific requirements of a country. In this paper, we give a direct equivalence between the codes which is only a final multiplication of the calculated area of reinforcement by a coefficient. That is why, with a great number of comparison between the countries, we can get all the equivalence coefficients which can be used at the end of a design in order to comply with the requirements of a given country. Thus, the researches may be extended to other structural members, kinds of buildings, load cases, etc. The creation of an equivalence big data of the trend-lines may give a simple way to obtain the equivalence between the previous codes.

5. CONCLUSION

Finally, we can give the general conclusion of this research. In flexure design, the results of rebar areas are roughly similar and, in a given comparison, the mean value of the calculated ratios is a very accurate approximation. Eurocode 2 is slightly more conservative than the other design codes. In shear design, the calculated ratios are located in an approximated range between 1 and 2. Besides, for a given comparison, the value of the calculated ratio changes a lot according to the value of the ratio span/spacing between beams. ACI 318 is mainly the most conservative design code.

Then, with the comparisons, we obtain the ways to give an equivalence between the codes. In flexure design, the results are very similar. So, the equivalence is the mean of the results. In shear design, the results of the calculated ratios are not close to a same value. However, we have shown it is possible to give the equivalence between the codes as a function in which the function is the calculated ratios and the variable is the span/spacing between beams ratio.

All of these results may lead us to raise the feasibility of a common international code. By admitting all the countries have accepted to follow the rules of one given code, the countries can still keep their current level of safety by using the equivalence results of this research. Going further in this kind of research by studying, for example, more structural members, sorts of structures or design codes, may allow us to create an international database which gives the equivalence ratio for a given case. This international code is not unique but common. The unicity is the requirements of each country.

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[7] American design code: ACI 318-M05, "Building code requirements for structural concrete", 2005

APPENDIX - A

NOTATIONS AND ABBREVIATIONS:

ACI or *ACI 318*	American concrete structures design code
$A_{s,ACI}$	area of flexure reinforcement according to ACI
$A_{s,EC2}$	area of flexure reinforcement according to EC2
$A_{s,GB}$	area of flexure reinforcement according to GB
$(A_{sv}/s)_{ACI}$	area of shear reinforcement according to ACI
$(A_{sv}/s)_{EC2}$	area of shear reinforcement according to EC2
$(A_{sv}/s)_{GB}$	area of shear reinforcement according to GB
b	width of the web
b'_f	effective width of flange
$C25$	concrete grade (cubic compressive strength = 25MPa)
$EC2$	European concrete structures design code (Eurocode 2)
d	effective depth of the beam
GB or *GB* 50010	Chinese concrete structures design code
h	depth of the beam
h'_f	depth of the flange
l_0	beam span
m	meter
R^2	coefficient of determination
s	spacing between shear reinforcement
s_b	center to center spacing between two beams