UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ETS INGENIERÍA DE CAMINOS, CANALES Y PUERTOS

TRABAJO DE FIN DE GRADO

Comparing the convenience of construction rules: FIB, EHE and EC2 applied to the Mahon airport arrivals viaduct (Balearic Islands)

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1. **Synthesis in all three languages:**

Títol i resumen en valencià:

Comparativa de la conveniencia de les diferents normatives constructives: FIB, EHE i EC2 aplicada a la plataforma d'arrivada de l'aeroport de Maó (Illes Balears)

El meu treball és un estudi que té com a objectiu el aclarir com d'adaptades están les diferents normatives al coneixement actual que tenim dels materials. Este projecte compara estes normatives amb uns experiments pràctics que ens permetran decidir quina de les normatives s'aproxima millor al comportament real dels models. A més es mostrarà una situació pràctica on es podrà desenvolupar l'estudiat.

Título y resumen en castellano:

Comparativa de la conveniencia de las diferentes normativas constructivas: FIB, EHE y EC2 aplicada a la plataforma de llegadas del aeropuerto de Mahón (Islas Baleares).

Mi trabajo es un estudio que tiene como objetivo el esclarecer cuán fieles son las distintas normativas al conocimiento que tenemos de los materiales. Este proyecto comparará estas con unos experimentos prácticos que permitirá decidir cual de estas se aproxima mejor al comportamiento real de los modelos. Además se puntualiza en una situación práctica que nos sirve para aplicar de forma detallada lo estudiado.

Title and summary in english

Comparing the convenience of construction rules: FIB, EHE and EC2 applied to the Mahon airport arrivals viaduct (Balearic Islands)

This is an investigation that searches to bring light to how up to date the different codes in regards to the knowledge we have of materials. This project will compare with practical experiments that will allow the decision of how close to the real behavior of materials each code stands. It will also be applied to a practical case that will allow an explanation of what's been analyzed.

2. Introduction

As a Spanish student who spent their last degree's year in Lyon (France), this document is redacted from the perspective of a totally interesting experience with regards to this project. I will work with the EHE mainly, the Spanish structural code yet I still hold hope that I might also extend my influence,meaning to travel for work and address diverse conflicts in different places and countries. The European Union, with their project of unity and cohesion, free travel and trade, gives me opportunities beyond what I could have hoped and thus comes into play the Eurocode 2 the one used in most of Europe during the exercise of our trade.

This last document was written in 2004 and because our understanding of the field is ever evolving, always absorbing new ideas and modus operandi it is imperative that those laws should change accordingly, reflecting the deepening of our knowledge as a society. Keeping the information updated is optimal for everyone dedicating their lives and efforts to this field because we all work on a budget and the responsibility is high, thus causing the making of structures to be a treacherous path, always on the search for efficiency.

To aid me on this quest I was introduced to HILTI, a German machinery company with an enormous involvement in the making of precast concrete structures and the pieces that compose them internationally. They helped in the making of this project by sending, as their representative Jakob Kunz, he was really helpful whenever doubts arose. As a specialist he gave really interesting and thoughtful insight on how the mechanisms in the structures analyzed work.

An update in the Eurocode is expected to happen anytime soon, this means that by doing this research one is gazing into future possibilities, hinting at what might happen and therefore bettering oneself for the future.

On a second part, the EHE the code mainly used in Spain with its variations from the eurocode, makes for an interesting foil. Something worth mentioning here is that the EHE has as of the release of this project stopped being the standard upheld in spain. The CTE, the new code, will start being legally upheld when the new year starts but at the beginning of this project, almost a year ago and a half it still wasn't. Commentators defend this CTE is even closer to the Eurocode so it shouldn't be an issue

This project will conclude with the analysis of a practical case in which this investigation could be useful

3. Problematic at hand

The mechanisms by which structures work are dependent on many variables and because of that slight changes may affect more profoundly than one would guess instinctively. For example the kind of aggregates, their shape and size will determine the angle of engrainment, and thus divert the way the force is transferred through the structure this way granting our structure a different grip onto itself. This variable alone would cause the resistance and path of failure to be significantly different and just like this there’s lots of variables.

One would think taking every level of detail would make for a more complete knowledge of the structure. Contrary to this, we know that the amount of variables we include in our calculations is tantamount to its level of complexity, so much so, calculation methods easily reach the point where they no longer are a straightforward and easy to use aid, people thought would help them calculate. This issue will eventually be solved through some assumptions and simplifications that might lead the structure to err, yes, but it will do so, theoretically, on the safe side.

This project is designed to analyze some of these assumptions in each of the laws, concerning the effect of punching shear breakage by contrasting them to the experiment done in the sharma publications. Later on a phisical case will be analized both to demonstrate the practical application of the matter studied and have the project be more diverse on its study of possibilities and circumstances.

This experiment hopes to simulate breaking of a slab by action of punching shear. This concept has diferent names in different languages but essentially it’s the possibility that at the point of maximum shear in a platform or a foundation. Where an elongated element meets a perpendicular structural plane.

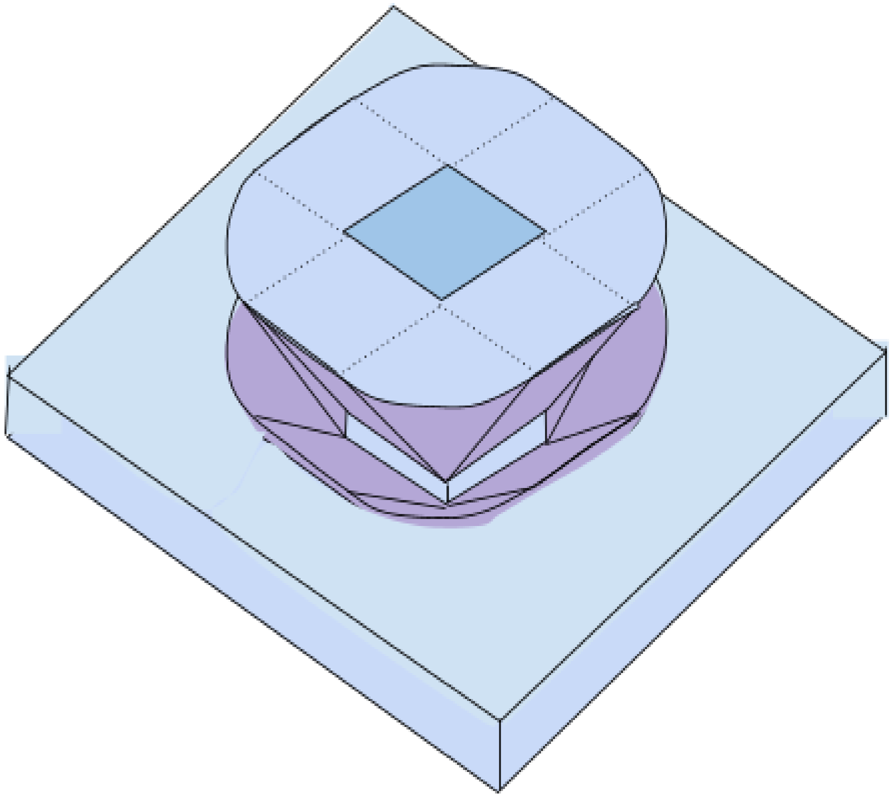


figure 1: punching shear break-out

The structure above creates a resistant mechanism oblique to the force to compensate for the lack of resistance to the concrete's traction. By splitting efforts it manages to resist. This is the strut-and-tie mechanism and it will be explained in the literary analysis .

The establishment of patterns and names would be a much appreciated tool when navigating this project. The problem is each code actually names concepts differently and so does the experiment. This has been problematic for my work but I will try to make it as clear to you reader as possible. I find this is an essential step in order to properly follow the development of this project. Since we worked throughout with several languages and with slightly differing terms for the same or similar concepts. On top of that, when working with people of diverse backgrounds I believe clarity to be essential.

On final drawing before this explanation is over we can see a hopeful rendering of the experiment, according to theory this should be the ideal final execution of the Sharma experyment modeled for reference. It serves us mostly as a way to put into context the previous figure soit can be imagined in the actual setup and make the following explanation more comfortable.

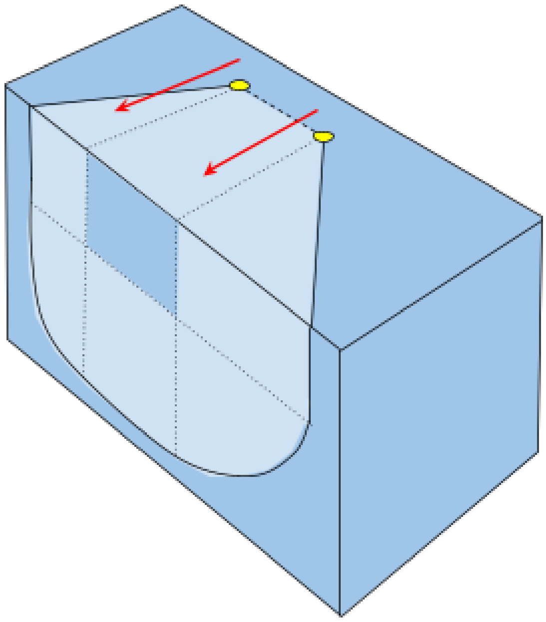


figure 2: 3D view break-out cone

In figure 1 we can see how the crack is represented through the line of the shift in color. We have, in a lighter blue, the piece that breaks off from the slab, represented in a darker shade. The angle at which it spreads, as we said before is malleable but the eurocode and the EHE assume them to spread at an angle of 26,565º ($cotg\theta = 2$). The Fib for example theorizes this to be 63,435º($cotg\theta = 0,5$) the fib model. On top of that the experiment assumes beforehand the cracks will spread at a ratio of $cotg\theta = 1,5$. This makes the results, interesting to contrast.

By running these numbers through some trigonometric rules we can get how the crack spreads. This is diverse and variable and each code takes the value they assume will work best.

But what exactly does this mean? For calculation purposes the half elongated along the point semi conical shape that would be formed will in these codes suffer simplifications like the one in figure 2 In some situations there will be points in which the shape is simplified to a square one as shown in the display.

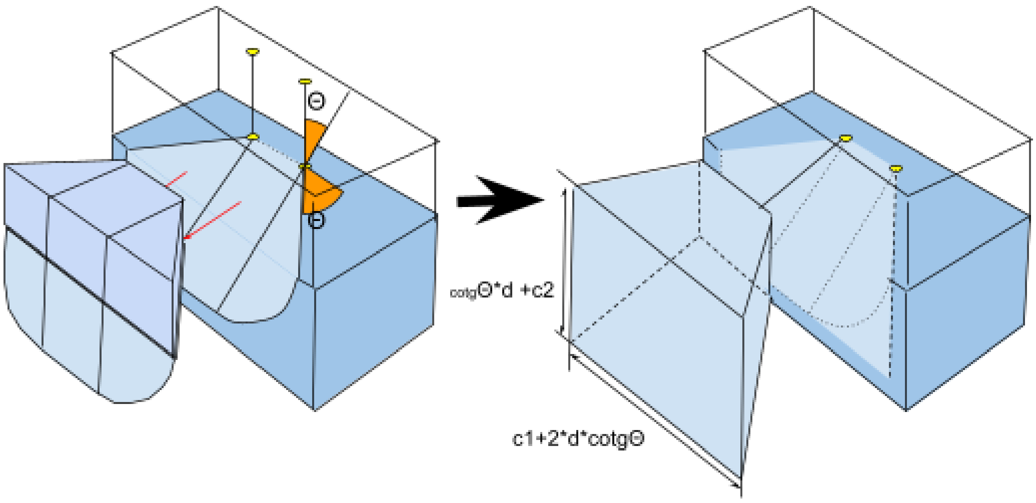


figure 3: sketch exemplifying the prism

This hypothesis works with the premise that the resistance of the concrete, which tends to be highest in the eurocode, is derived from the shear planes from below and on the sides. The simplification does alter the values like this, with the math shown in the annex-1 calculated for a $cotg\theta = 1.5$:

1. Real prism area: $approx.\ (9.5 * h + c_2) * h$

2. Simplified: $approx.\ (5.4 * h + c_2) * h$

But the codes don't use these areas that would in some cases become too strenuous to calculate. They use the u_1, the length of the perimeter the cracks would make theoretically. This is called a control perimeter. And so the real importance of the previous values comes with the proportional value they hold to their u1. And we can see that the proportion is mostly maintained even landing slightly on the conservative and not that further off, and h is usually much bigger than c_2, the simplification should be safe.

From this premise they both equate it to a proportion of the surface area moved, which should be proportional to the previously mentioned area.

Other assumptions, specific to each literary source will be made, with that in mind, it's only natural to begin by explaining the main literary sources, what their take on this experiment should be and how the contemplation of these sources has helped concoct this project.

4. Literary review

a. The strut-and-tie method

The codes are useful and they all align in thinking that the strut-and-tie is a useful method to simplify the multitude of forces and factors that intervene in the physical process any structure undergoes as it faces said force. This method formulates an abstraction that works by stating that some elements will work in compression and others in traction in this case the concrete being more fit to hold compressions whereas the steel is isotropic. This means it holds similar properties in all directions and by process of elimination it leads us to a place typically in an area where it will face the tractions. The difference in price between them justifies this ordeal.

This mechanism works as shown in the next figure:

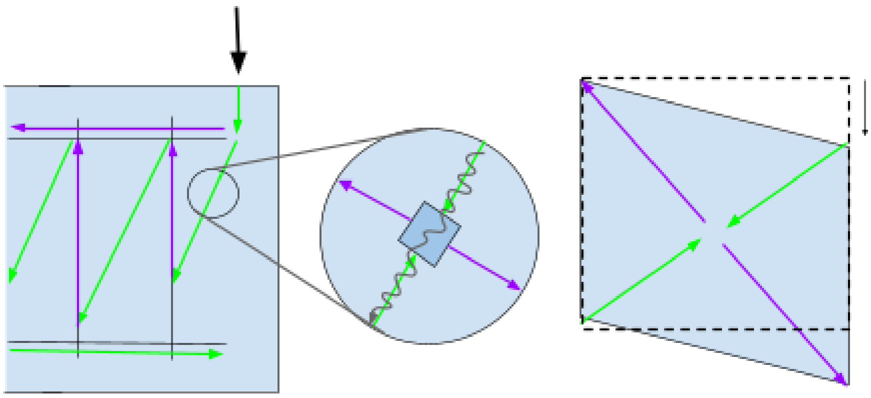


figure 4:strut-and-tie design

This behavior is coherent with the observations taken both in and out of this work. On top of that it's really useful to think like this because the Concrete which we deem most dangerous (because of it's more explosive breaking patterns), becomes the protagonist. Concrete is the material we handle the most and in this kind of situation usually suffers traction fissures aligned to the plane we compose the strut in. This strut is a name for the ideation of a discrete compressed element.

Well, perpendicular to it the concrete suffers tractions that will bring about its failure.

The steel has its own method of failure but due to its plasticity, when it finally arrives it will have by then announced the structure's demise. The steel will deform as it reaches its limit and so in most conceivable scenarios the concrete will crack way before the reinforcement snaps.

In figure 1 the tractions in purple and compressions in green can be appreciated. From the diagram on the right we can appreciate how and why the cracks open.

b. Eurocode

The first one is, due to its popularity in France, the eurocode, the axis by which most European countries check the resistance of their concrete structures. Some countries use it as their main way to dimension structures and It is widely popularized, especially in France, where I, the author, was studying.

The first item the eurocode evaluates, when referring to punching shear is the concept of control perimeter. It's a tool to determine how much of the contour around the application point of the force can be used to resist the efforts. It doesn't equate to a real resistant mechanism but it is proportional to the resistance. Other codes will take the same approach with slight variations.

On the eurocode the basic control perimeter exists at a distance of twice the thickness of the slab from the column the force comes from.this would mean the force spreads at an angle of 26.565º this is lower than it would on a conventional shear study. This difference is because conditions near columns are better controlled and the sections are acting more unified and confined in the section in a tighter area.

It handles the immediate conflict of different d on ortogonal directions, the compression arm length in the two axis by stating one could take it as the average of those.

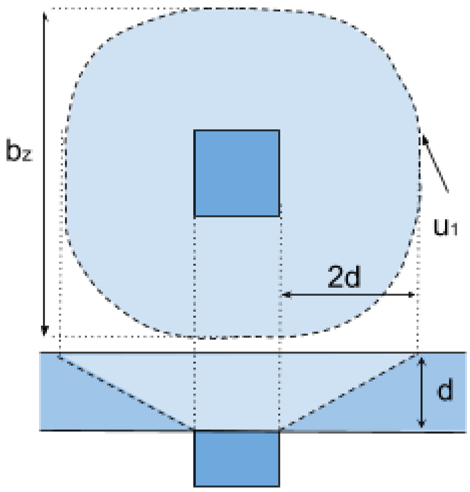


figure 5: control perimeter

$$v_{Ed} = \beta \frac{V_{Ed}}{u_1 d}$$ (formula 6.38)

- $d_{eff} = \frac{(d_y + d_z)}{2}$ (formula 6.32)
- General formula for eccentric effort

  $$\beta = 1 + k\frac{M_{Ed}}{V_{Ed}} * \frac{u_{1^*}}{W_1}$$ (formula 6.39)

  - For rectangular edge columns

    $$W_1 = \frac{c_2^2}{4} + c_1 c_2 + 4c_1 d + 8d^2 + \pi d c_2$$ (formula 6.45)

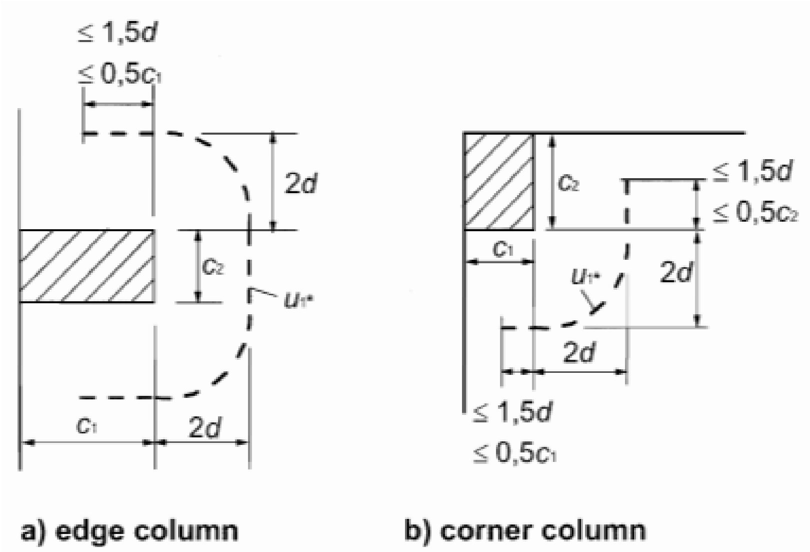


figure 6: Basic control perimeter

- For rectangular inner columns

$$W_1 = \frac{c_1^2}{2} + c_1 c_2 + 4c_2 d + 16d^2 + 2\pi d c_1$$

c_1/c_2	≤ 0,5	1,0	2,0	≥ 3,0
k	0,45	0,60	0,70	0,80

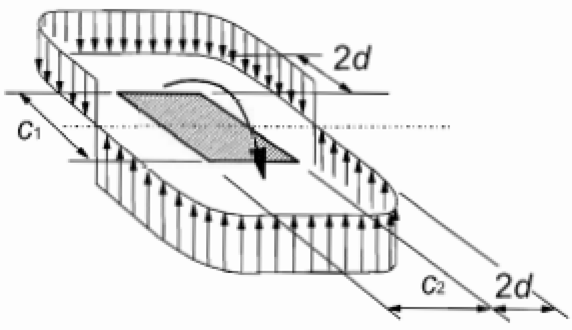


figure 7: Shear distribution when unbalanced.

- When there's excentricities in both directions

$$\beta = \frac{u_1}{u_{1^*}} + k \frac{u_1}{W_1} e_{par} \qquad \text{(formula 6.44)}$$

  - e_{par} eccentricity parallel to the edge

- $v_{Rd,c} = C_{Rd,c} k (100 \rho_1 f_{ck})^{1/3} + k_1 \sigma_{cp} \geq v_{min} + k_1 \sigma_{cp}$ (formula 6.50)

- $k = 1 + \sqrt{\frac{200}{d}} \leq 2 \; [d \; in \; mm]$
- $\rho_l = \sqrt{\rho_{ly} * \rho_{lz}} \leq 0,02$

When calculating this value it's possible to take the average distribution and calculate it in an area of (column width+3d each side)

- $C_{Rd,c} = 0,18/\gamma_c$
- $v_{min} = 0,035k^{3/2}f_{ck}^{\;1/2}$
- $k_1 = 0.1$

These last three are values recommended values, there are specific national annexes that contain more specific values

An annotation I find necessary would be the axis are turned from what I usually work with, here it considers the axis in the horizontal plane or plane of study to be y and z and so it was confusing to translate some of the concepts as they were being narrated.

c. Fib model code

The second is the fib model, a code published in 2010 that hopes to expand on the information dealt by the eurocode. It takes a different approach in some regards and is considered slightly more precise when calculating certain structures. This document should help put that assumption to the test.

This code tends to be a bit more generous when considering resistances.

Its resistances are obtained as the addition of the contribution of both the concrete and the reinforcement and even though both are reduced, the sum tends to reach bigger results,

$b_0 = \frac{V_{Ed}}{v_{perp,d,max}} \rightarrow V_{Ed} = v_{perp,d,max} * b_0$ (formula 7.3-57)

- $b_0 = k_e * b_{1,red}$ (formula 7.3-58)

  This is the value we called u_1 on both the eurocode and the ehe

  - $k_e = \frac{1}{1+\frac{e_u}{b_u}}$ (formula 7.3-59)
    - $e_u = \sqrt{e_x^2 + e_y^2}$ (from figure 7.3-27)
      - $e_x = \frac{M_{Ed,x}}{V_{Ed}}$
      - $e_y = \frac{M_{Ed,y}}{V_{Ed}}$
  - $b_{1,red}$ is the b_0 but removing a proportional piece accounting for openings or inserts.

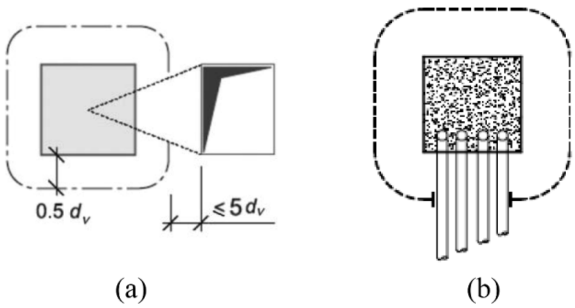


figure 8: reduced u1

- $V_{Rd,c} = k_{\psi} * \frac{\sqrt{f_{ck}}}{\gamma_c} * b_0 * d_v$ (formula 7.3-60)
  - $k_{\psi} = \frac{1}{1.5+0.9 k_{dg} \psi d} \leq 0.6$ (formula 7.3-63)

- $V_{Rd,s} = \sum A_{sw} k_e \sigma_{swd}$ (formula 7.3-66)
  - $\sigma_{swd} = \frac{E_s \psi}{6}(1 + \frac{f_{bd}}{f_{ywd}} * \frac{d}{\varphi_w}) \leq f_{ywd}$ (formula 7.3-67)

d. The Spanish Structural Code (EHE)

Since this is the prevailing document used in Spain to check the validity of structures it was only natural it was also included in the project, if only to serve as a local foil for the exercise.

On a particular note it seems to be the code I, as the author of this document, will be using the most in my life. So it's only best to use it since I really did become familiarized with it during my last years studying in Spain and one can only hint at the future that's to come. The EHE takes a similar approach to that of the Eurocode2.

First it states a rule that will account for eccentricities and the type of distribution. (page232)

$\tau_{sd} \leq \tau_{rd}$

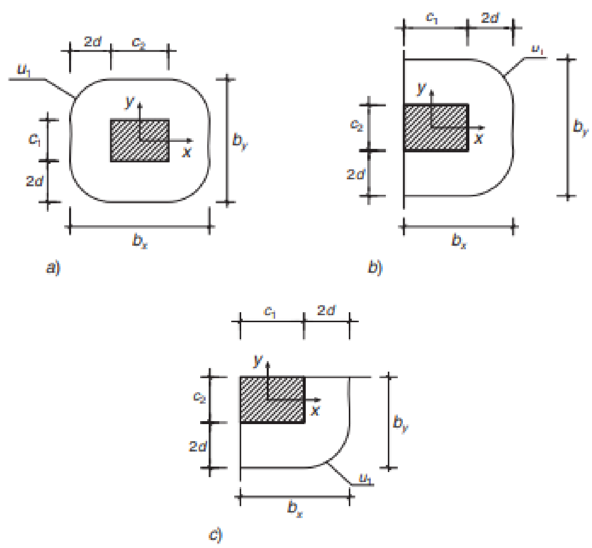
- $\tau_{sd} = \frac{F_{sd,ef}}{u_1 d}$
  - $F_{sd,ef} = \beta F_{sd}$
    - $\beta = 1$ if we can assume that there are no moments transferred
    - $\beta = 1,15$ if the charge is centered
    - $\beta = 1,4$ if the charge is located at an edge
    - $\beta = 1,5$ if the charge is located on a corner
  - u_1 This dimension is defined as being the external perimeter in the following drawing. This is obtained as twicearea contained inside the perimeter formed by the column plus twice the thickness of the slab, this thickness is written as d in the figure. This follows the conical premise and assumes the fissure to be at maximum spread $cotg\theta = 2$
  - 

figure 9: Critical surface

- d refers to the actual thickness of the slab

- $\tau_{rd} = \frac{0,18}{\gamma_c}\xi(100\rho_l f_{cv})^{1/3} + 0,1\sigma'_{cd} \geq \frac{0,075}{\gamma_c}\xi^{3/2} f_{cv}^{\ 1/2} + 0,1\sigma'_{cd}$

  This is the resistance of the concrete when there is no resistance on the z axis
  - $\xi = 1 + \sqrt{\frac{200}{d}} \leq 2$
  - γ_c equals 1.4 in our case
  - $\rho_l = \sqrt{\rho_x \rho_y} \leq 0,02$ those being the proportion of reinforcement per area in the x and y direction. Obtained by using the width +3d on each side times h.
  - $f_{cv} = f_{ck} < 15N/mm^2$
  - σ'_{cd} in our example it's 0 and has only an axis but it's calculated as the average of the two directions, using 3d+width times h.

- $\tau_{sd} \leq 0,75\tau_{rd} + 1,5\frac{A_{sw} f_{y\alpha,d} sin\alpha}{s^* u_1}$

  When there is shear armor.
  - τ_{rd} is calculated in this case without the $< 15N/mm^2$

From this development we get that there is no simplification on the mechanism the force will take and we get a straightforward approach for the maximum effort.

e. The Sharma publications

This is an article in two pieces, narrated through two publications released in consecutive years. The first one explaining the experiment we will be referring in the following section of the project. In it, it details the conditions in which the tests were executed. The two publications are written by Akanshu Sharma, from whom they receive their name and were made in 2016 and 2017 respectively. Both were redacted for the wiley library. This is an online library created to host really diverse research documents. From these, the values obtained in an experiment that forced different slabs to their breaking forces were gathered and afterwards contrasted to the ones obtained from both codes.

The objective for which this archive was included is to serve as a metric to lay the ground rules when evaluating our codes. With this we will obtain a coefficient of excess. This is how much would in this conditions overshoot the resistance of the structure.

This experiment took a slab built with four different anchor distributions and took them to their breaking point. There is a catch for the slab is not acting as a slab itself but as a mechanical substitute of a different slab oriented in a perpendicular plane.

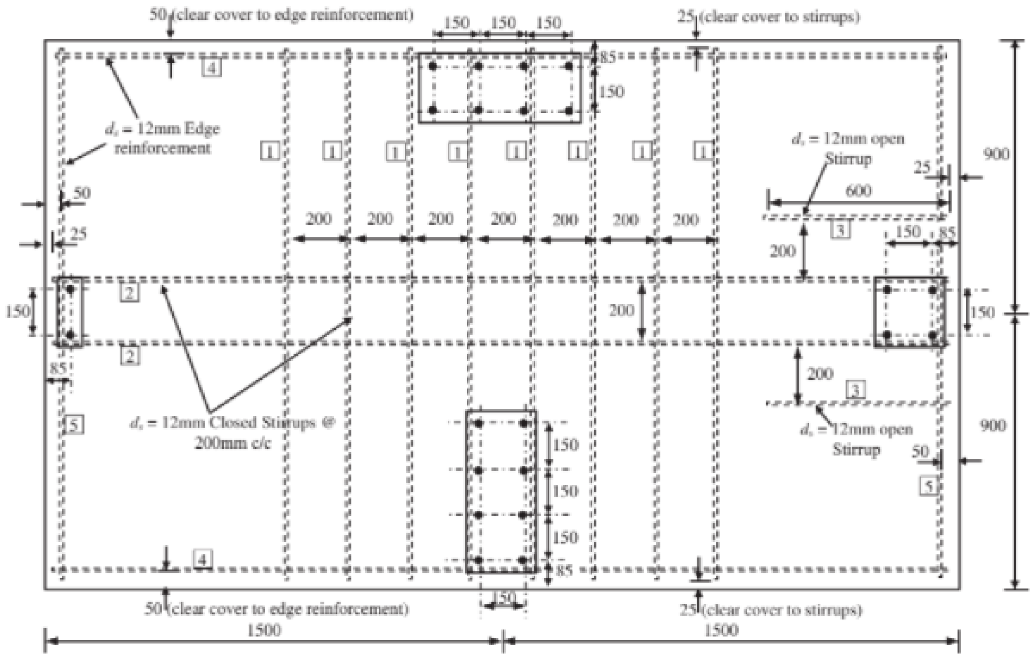


Figure 10: Experiment display

On figure a typical display for the experiment can be seen. This would be broken four times in the direction going out of the slab. The reason why might not yet be apparent. Twelve slabs were made, all with this anchorage distribution but executed three times for each type of edge reinforcement.

These edge reinforcements were:

1. Without edge reinforceement
2. $\phi 12\ mm$
3. $\phi 16\ mm$
4. A bundle of $\phi 16 + 14$

About the anchorage distributions, they each want to represent a different type of slab but using a much more limited space and therefore a smaller budget. But it takes an abstraction of shape that is narrated in the following figure.

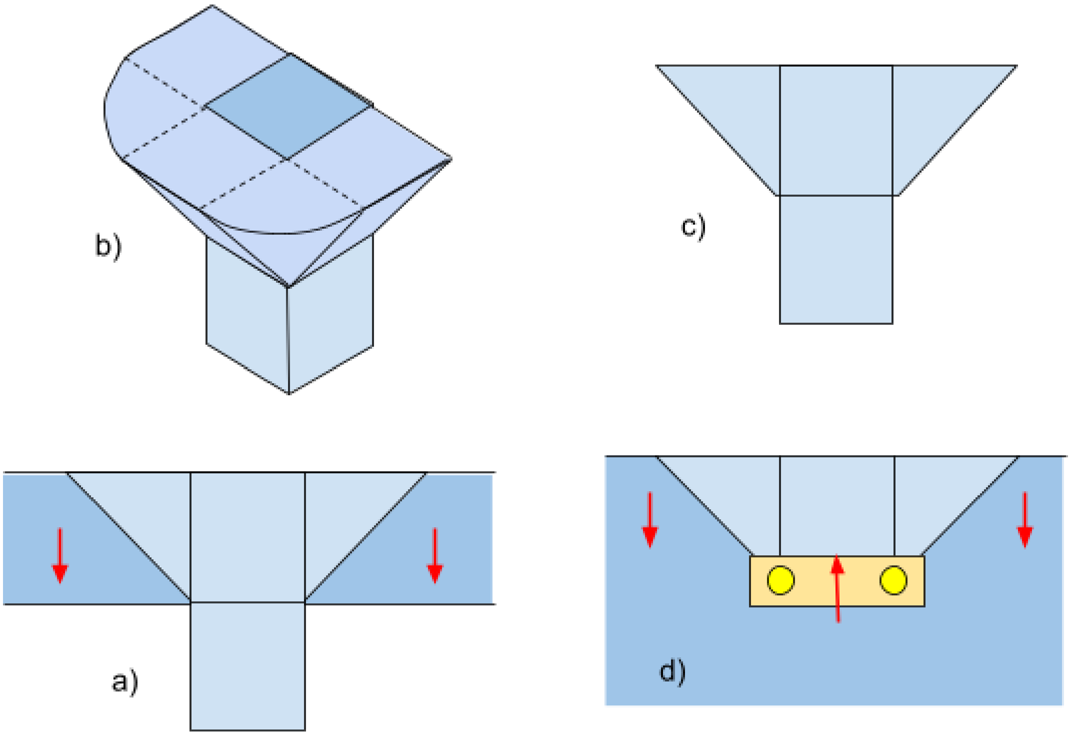


figure 11: development of the experiment

Represented in figure x we can see the steps taken to go from the situation, efforts applied onto a column to the approach the experiment takes.

a) Typical situation in which an edge column is resisting shear influence from a platform.
b) This is the theoretical break-out structure in this scenario, I have removed the platform to have a clearer view of that one side of the mechanism. Because of the difference in scale and the particular angles the structure takes any 3D representation including both would lack clarity.
c) The previous structure as seen from behind.
d) The experiment distribution (1x2) as the experiment executes it. This displays a similar enough situation so as to consider the transformation valid.

Some concerns with the transposability of the experiment are:

First off, do the stirrups have enough grip on the structure so as to consider the effort displayed here as properly distributed in this shape. These stirrups are round studs $\phi 22$ welded onto a thick plate. They are composed of a shaft of 165 mm and a head and together they have an effective length of 190 mm.

If we just assumed they work as separate efforts, their cones of influence (at $cotg\theta = 1.5$ meet at 50 mm from the stirrups, in all distribution cases before reaching the end and in the worst case proportionately, the 1x2 distribution they have a 40% intersection which should be more than enough.

Second concern would be more straightforward, won't the length of concrete in between the stirrups react to the effort affect the experiment? To this, it is a reasonable assumption that concrete subjected to pure traction with no reinforcement to aide it shouldn't amount to a significant margin of error, all things considered.

Now, onto the experiment's distribution cases, they are:

- a simple row with two anchors
- two rows with two anchors each
- two rows with four anchors each
- four rows with two anchors each

From these four we contrasted against the first three as recommended by Fabien Delhomme, the last one would be considering a platform 535 mm thick, useful maybe for a foundation slab but probably less useful on the long run and the margin of error for the actual control perimeter became too high making the resistant mechanism a little obscure. Since the experiment acknowledges this issue (as shown in figure x right next) and the time was pressing it was decided the analysis of that case could wait for a future retake of the project.

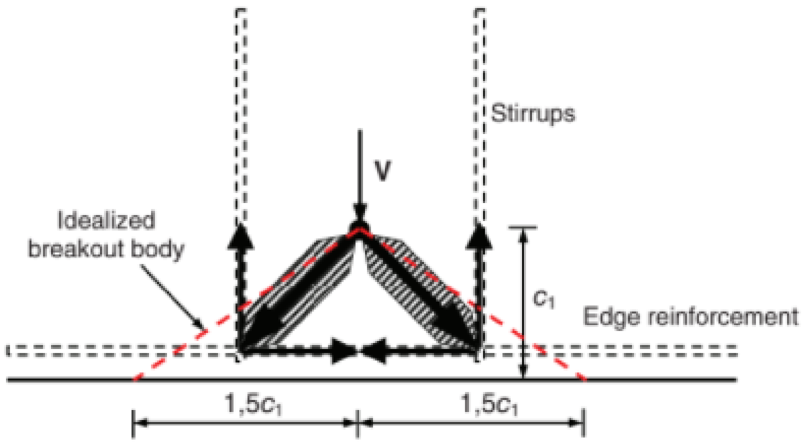


figure 12: force distribution according to the experiment

.

Here is an example of the strut-and-tie method, acting as tie the reinforcements in both directions and as strut, the concrete.

The anchors, in the cases where they are stacked are set like that to one against the other acting as if they were a distributed load and thus they both prevented an excessive compression of the concrete between them and also prevented a momentum induced by the resistant mechanism possibly dislodgin the stirrups and impeding the proper developing the experiment. This way the counter-momentum that can be induced onto the platform is much higher. For ideal behavior the force should be applied wi

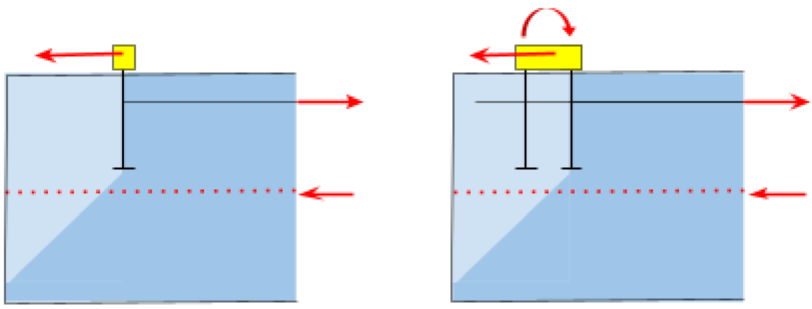


figure 13: effect of the multiiple rows of stirrups

Whether the changes in the code are convenient and safe will come from evaluating the contrast in these cases.

A particular note on my part would be that contrasting the resistances against the reinforcement area instead of diameter might be better but since the Sharma publication does it by diameter it will be kept that way.

The experiment's design was like this:

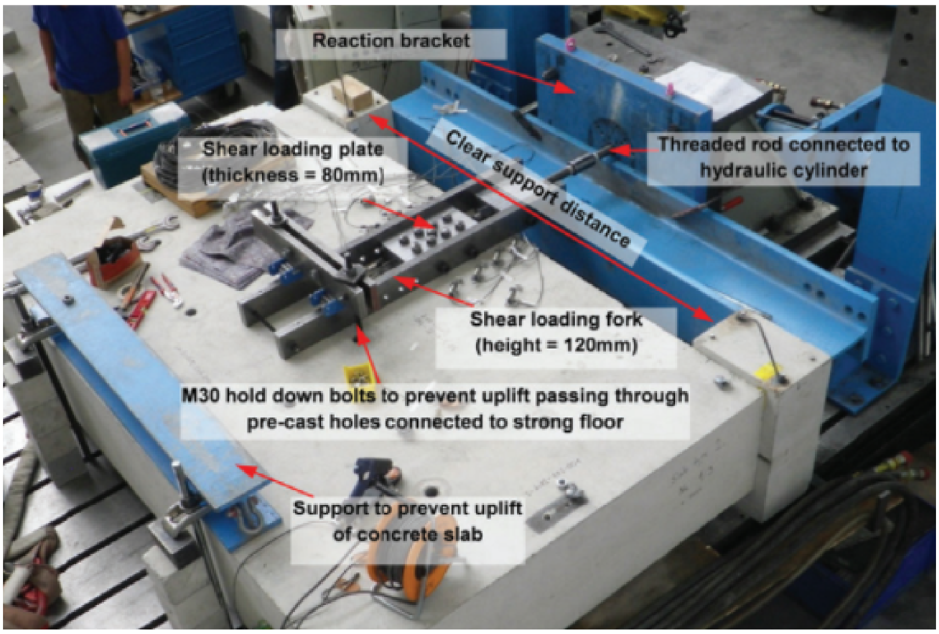


figure 14: Experiment setup picture

From this setup the hydraulic press pushed on the plate and brought the structure to a breaking point for all of the cases. From this we get the results we will analyze in the following part of the project.

It can also be appreciated from this picture that it was much easier with this display to rotate the slab instead of building separate ones for each case. Also, by having a display like this, one could let the structure´s sheer size and weight be an effective measure to distribute the efforts, becoming therefore safer and more controllable.

The particular display leaves a slight doubt on whether to consider c_1 to be taken from the effective length of the anchor or the length of the shaft but I trust the experiment did its job when determining that value was “effective”.

5. The experiment’s comparison

This experiment works like so, and this shape will represent the resistant mechanism in place.

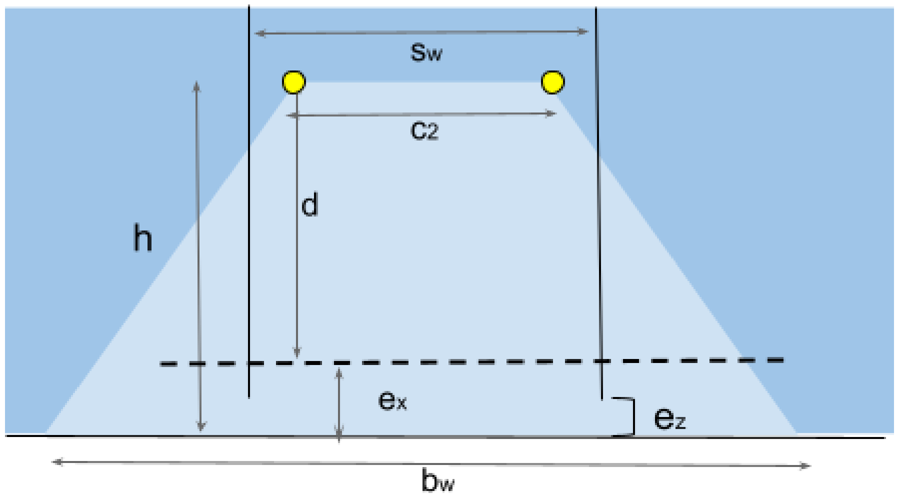


figure 15: break-out cone (up view)

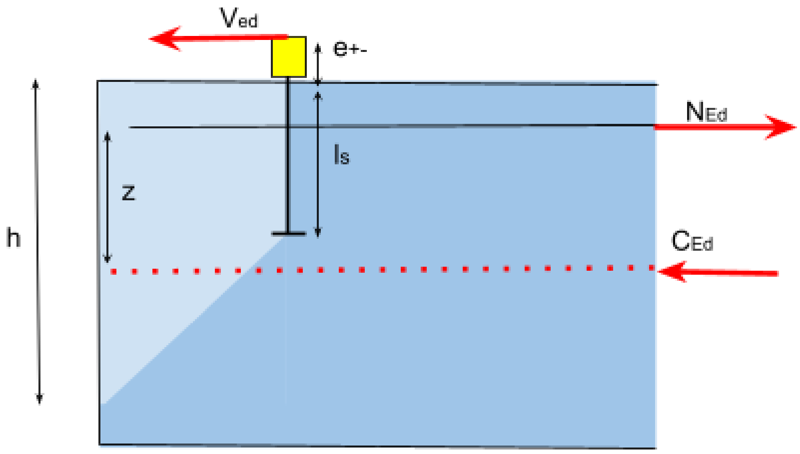


figure 16: break-out cone (side view)

In figure 9 and table 2 the experimental results obtained in the Sharma publications are shown, this will be contrasted against the values we would expect in those situations introducing the corresponding data into the corresponding formulae presented by each code.

Here in figure 9, a plotting of the average results of three experiment distributions can be seen. The three regarded as having top importance were chosen and displayed in a graph that places as its two axis: The diameter of the bars resisting the effort (x axis) against the traction resisted by the model (y axis).

There existed a fourth distribution the 2*4 but it was decided it didn't bring so much to the project.

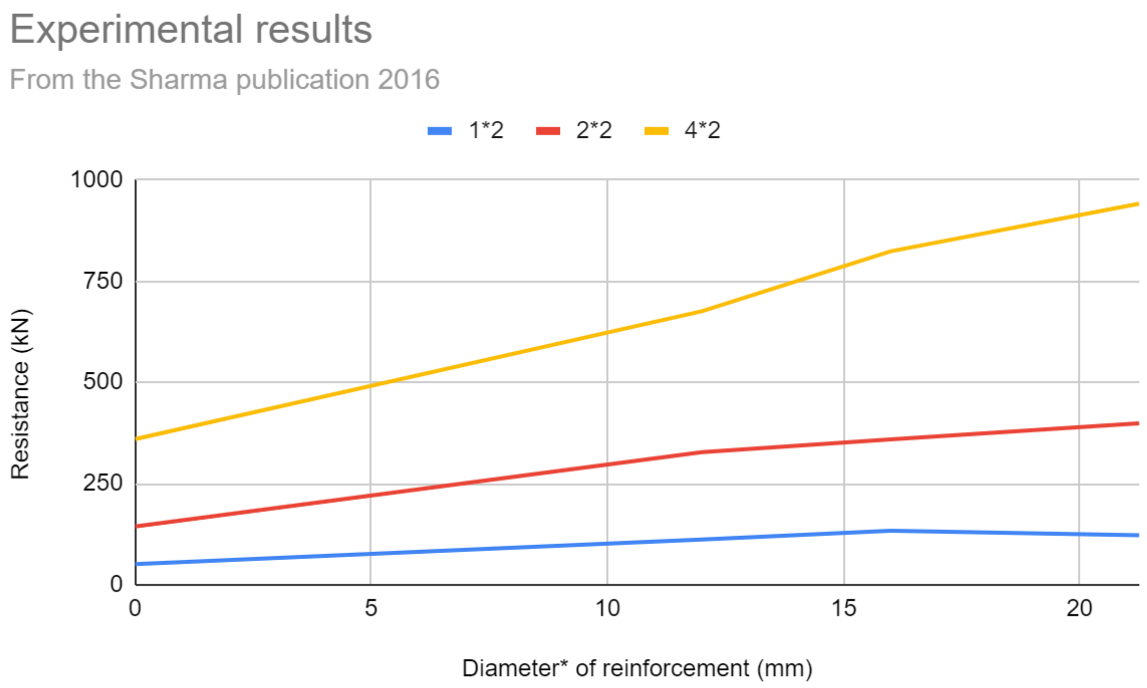


Figure 17: practical results

For clarity, displayed in table 2, are the numerical values the averages from the number of times the experiment was repeated.

		Diameter of reinforcement (mm)			
	Values (kN)	0	12	16	16+14
Experiment name	1*2	51,2	111,7	133,5	122,7
	2*2	144,3	327,5	359,5	399,2
	4*2	359,9	675,8	823,8	941,3

table 18: Experimental results

Analytical results are bound to differ from the reality, if anything, at least for safety reasons there are coefficients applied onto our numbers due to the different anomalies that our trade implies. This situation represents yet another hurdle in the investigation.

To show the results, graphs for the three experiments have been gathered: 1*2 or single row, double anchor; 2*2 or double row two anchors each and 4*2 or double row four anchors each, considering for the second and third, the breaking of both rows as the two are useful elements of study.

The separate effect of force on each row is an event that will impact the results obtained both for pull-out and for a hypothetical cutting of the bar both are situations that would be affected by the “other” force.

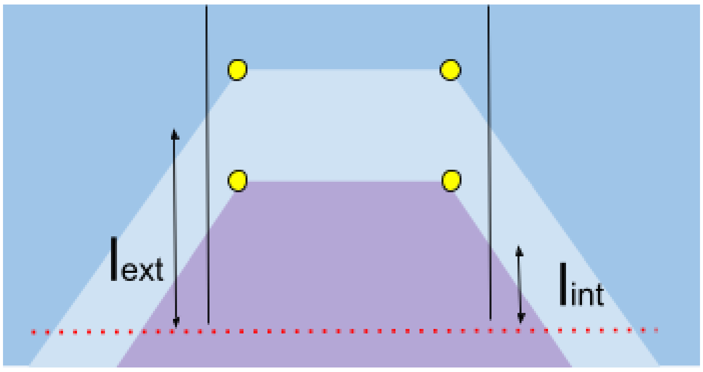
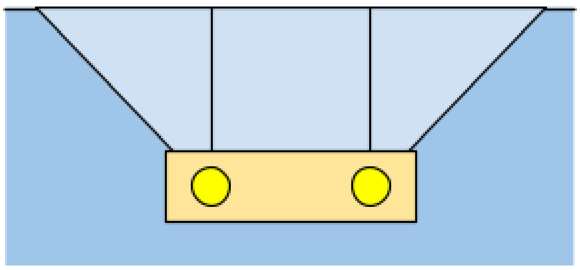


figure 19: the breakout areas

Thus the lilac area in figure 10 would be holding, assuming we’re dealing with a rigid system, more force than its light blue counterpart. Since the reality is really different and all bodies behave to a degree elastically, the second row is actually less constrained than the second, plus the displacements the force causes are compounded to those of the first row, it becomes more adaptive and is allowed to absorb more easily deformations, therefore to a unified deformation it would be taking a much lower portion of the charges.

a. Single row, double anchor



$c_1 = 190\ mm$
$c_2 = 150\ mm$
$h = 85\ mm$
$d = 35\ mm$

	Diameter (mm)			
1*2 Vmax (kN)	0	12	16	16+14(21,26)
experimental	51,2	111,7	133,5	122,7
eurocode 2	6.901	13,291	13,607	13,607
fib	35,8	83,8	83,8	83,8
EHE	15,172	15,822	17,498	20,429

table 3: results for the first experiment

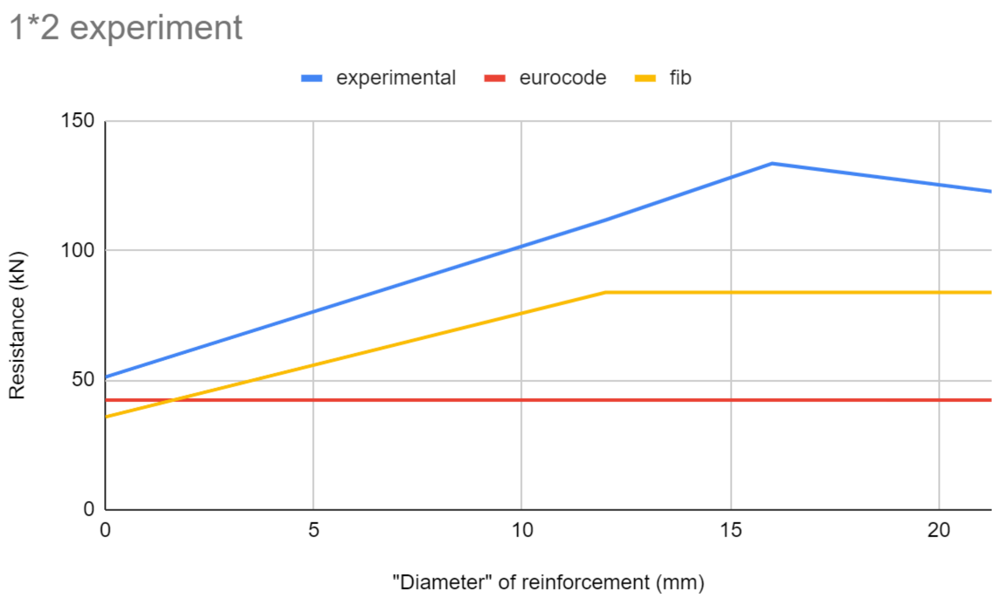


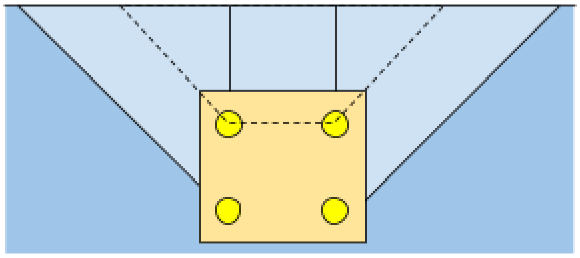
figure 10: the 1*2 results

In this one we can see the fib follows an appropriate correlation to the one obtained through the experimental values, while the eurocode, since it only takes into account the concrete value, the biggest, does not correlate.

It can also be appreciated that the fib is slightly lower in the beginning and the proportion to the experimental result is kept towards the first mark, the ϕ12, where it stagnates until the last value. This is because at this point the maximum considered by the fib is reached. This means that the force of the pull will break the concrete by compression. This is reasonable because the reinforcement is standard sized whereas the edge distance and therefore the section a slab would have is minuscule.

This will be the only example in which, since there is only one row, no doubt about the origin of the resistance will arise.

b. The 2*2 experiment



$c_1 = 190\ mm$
$c_2 = 150\ mm$
$h = 235\ mm$
$d = 185\ mm$

Next we have the 2*2, theoretically the resistance to crack should come from only the front row and therefore be the same as the 1*2 experiment but it stands to reason that before cracking, the force should be distributed as the front row plus some of what the back row can hold.

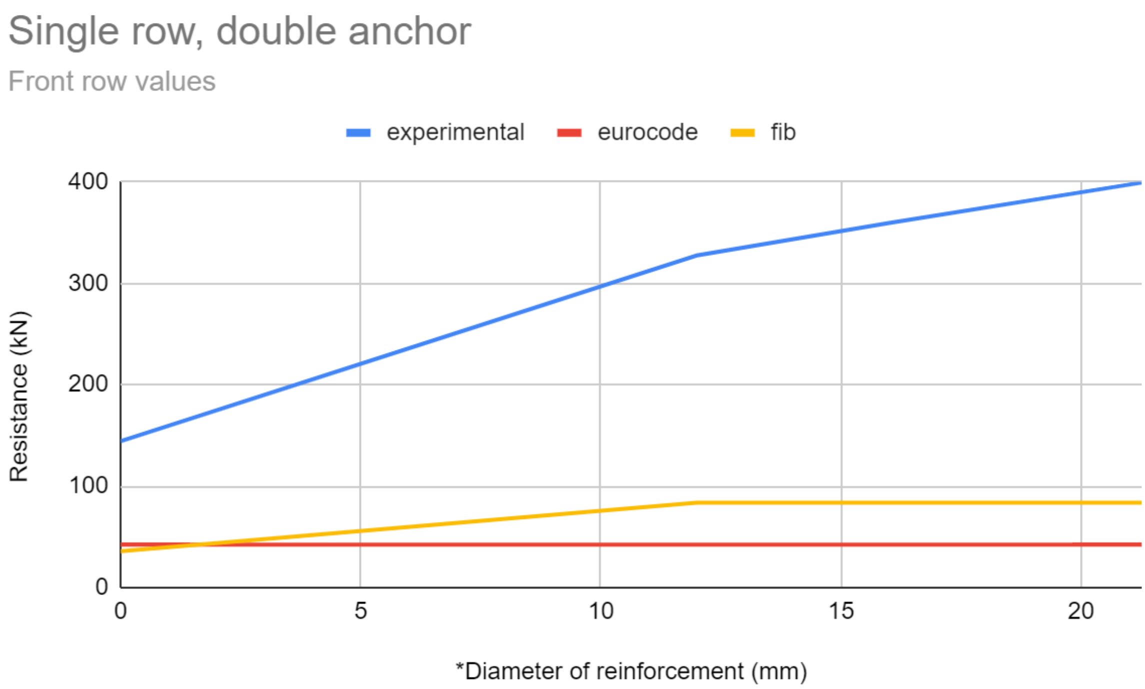


figure 20: 2*2 front row results

From this we can infer that the breaking mechanism wasn't exactly as we had imagined, only front rows doing all the work. So it stands to reason to contrast it with the back rows.

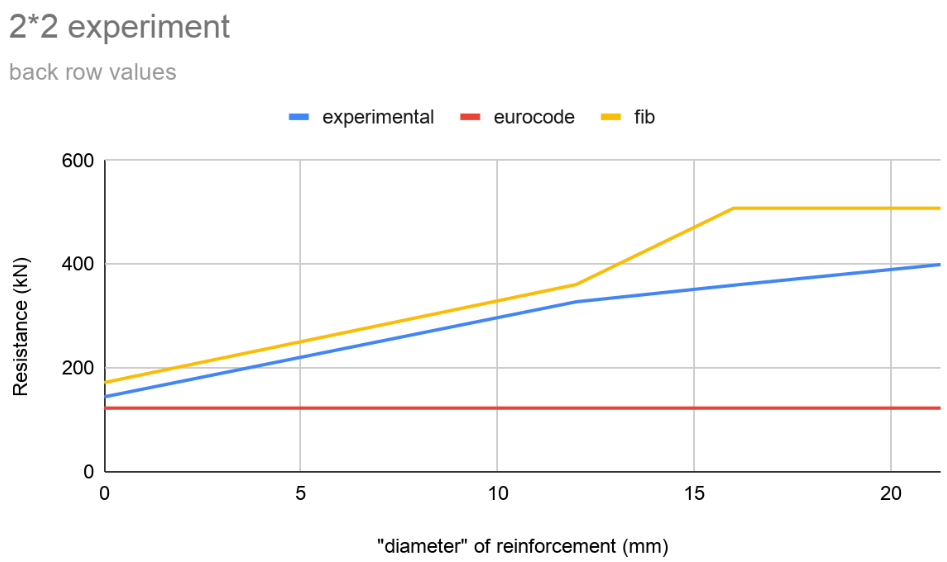


figure 21: 2*2 back row results

This second graph has a peculiar shape regarding the fib shape. There´s little data but it seems to show quadratic growth previous to the stagnation. This was to be expected to some degree but normally it should not be as noticeable. In other cases the compression value is so low that the value for ϕ12 has already reached it, but it seems that in this case it was given more room.

This results are merely orientative because the front row will theoretically always break first but we can see that even though the fib model surpasses it and the eurocode stands a lot closer the values are a lot more similar, this leads to the conclusion that a proportion of the force is shared through the whole structure even though it will end up breaking through the front row.

Diameter (mm)	0	12	16	16+14 (21,26)
experimental	144,3	327,5	359,5	399,2
eurocode	118,004	181,7559178	200,002	219,851
fib	171,9	360,8	507,73	507,73
EHE	206,162	213,190	234,543	271,907

table 4: 2*2 values

In this case if we consider the front row, the results expected are safe but really distant from the practical values, on the contrary, these values can be excessive in the case of the fib as it should be, addition, though it might seem convenient for the eurocode is unreasonable because of the tension distribution.

This, exemplified by: hanging two things from a rope at different points of it only adds the load without increasing the resistance.

Observing the breakage mechanism and the values obtained it's reasonable that not all rows act at the same time and to their specific limit simultaneously so I decided to devise a coefficient that would multiply the back rows in order to approximate what percentage acts in each case for future situations.

Using this formula

$$coefficient * Back = Experimental$$

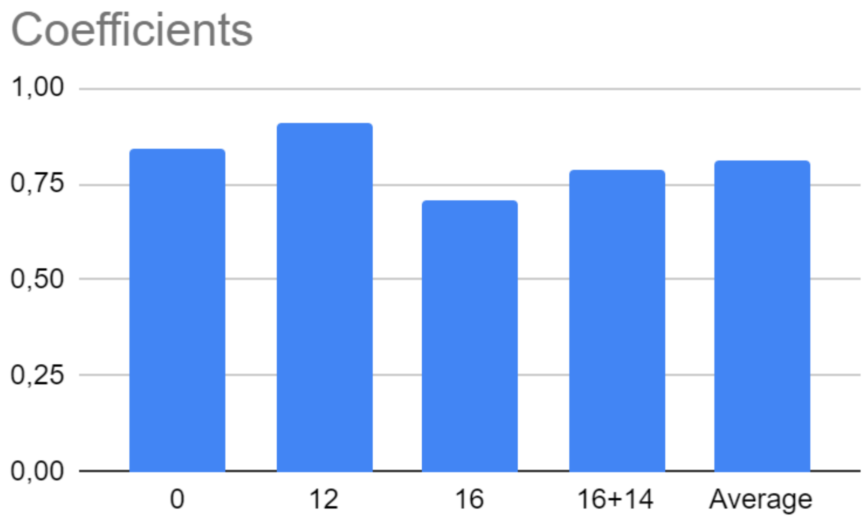


figure 22: Coefficients compared

From this fairly small set of data nothing definitive should be guessed but to entertain the idea: the average stands at 0.8104, with a variance of 0.0844, which is a mildly low value meaning a pattern should be reasonable to take, more data considered.

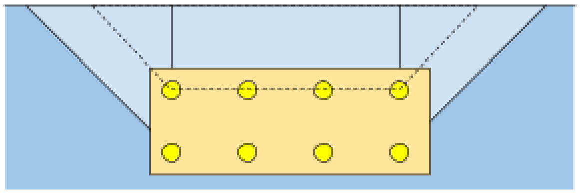
The variance is obtained using the equation $s^2 = \sigma = \sum_{1}^{n} \frac{(X-\mu)^2}{n}$

This consideration is a bit risky because codes like this try staying behind to remain safe even when the engineer takes the laws at face value. This coefficient, to be put into effect would need to have a semi probabilistic reduction so as to hold, perhaps 95% of the cases like in other values.

If we extrapolated the distribution to behave like a normal one, then this value would be of 0,6715

There are several instances, specially when comparing values without reinforcement or with no slab thickness in which the values the codes point out even surpass the experimental ones. This is an intolerable matter because even though under normal circumstances these circumstances wouldn't happen they stand on the side of uncertainty. Putting every user in danger.

c. The 4*2 experiment



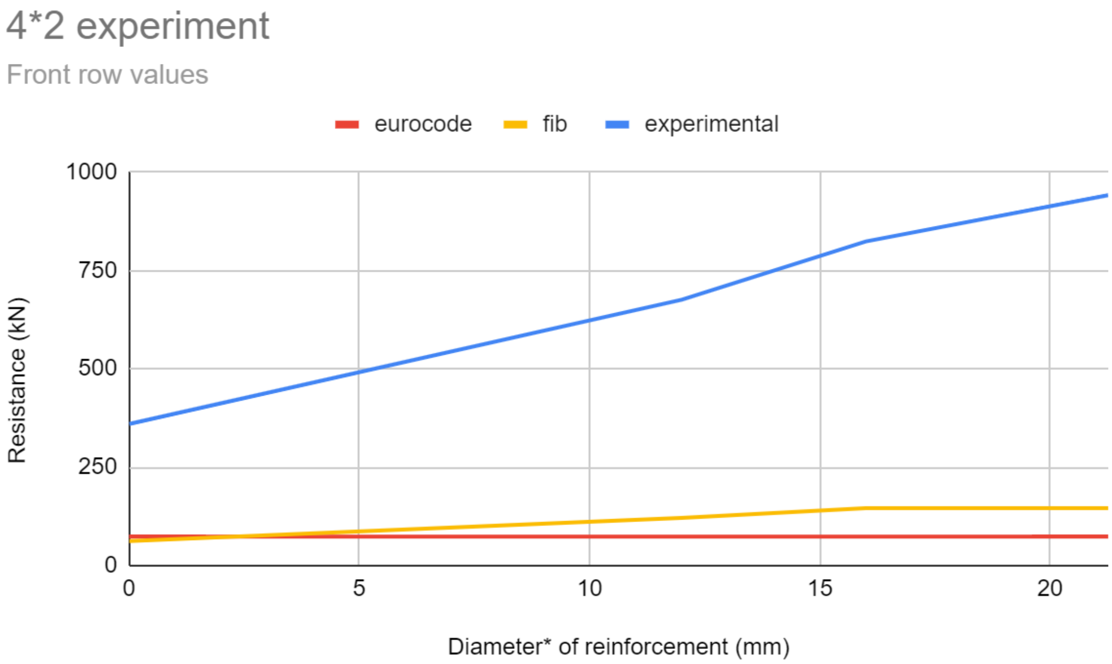


figure 23: 4*2 front row results

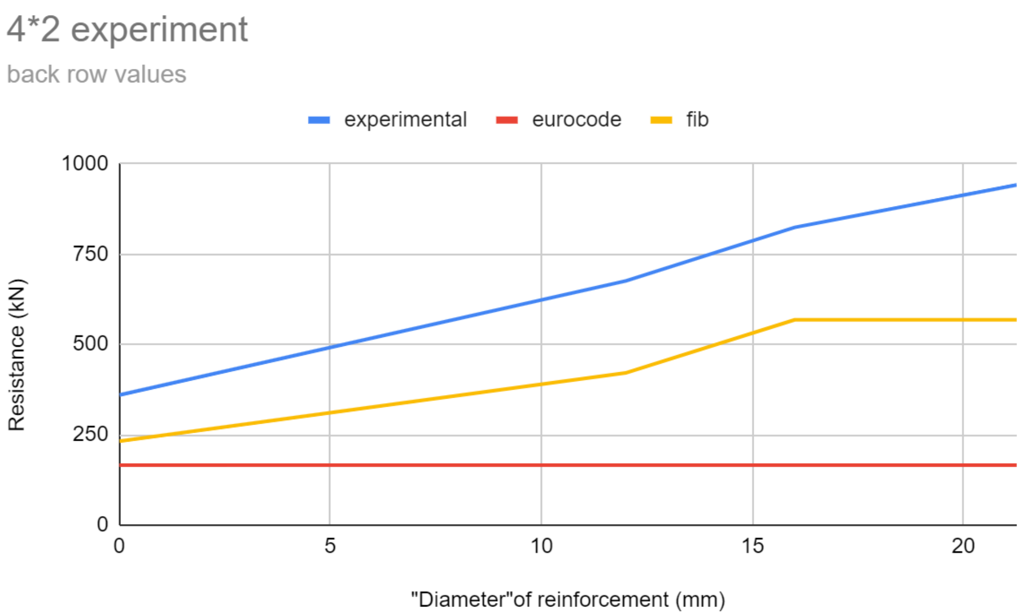


figure 24: 4*2 back row results

diameters (mm)	0	12	16	16+14(21,26)
experimental	359,9	675,8	823,8	941,3
eurocode	151,994	225,951	248,621	273,285
fib	232,22	421,12	568,04	568,04
EHE	251,471	256,032	278,957	319,074

table 5: 4*2 results

These values show surprising results. First the eurocode is not even close to the value, but also the fib stands much further than expected. The results in the back rows also stand at a safe distance to the experimental values, this means that the values are not at an unknown point within our expectations like before, but beyond our expectations. The previous coefficient logic is not applicable in this case

This peculiarity is either because the fib loses precision when faced with really high values, because it chooses to generously stay on the safe side in said cases or because actually the problem is not with high values but with anchor distributions this big.

It is necessary considering that, having the structure be this wide, it is natural that the transfer towards the back rows is higher than in the previous set up.

6. Practical example, Maó's airport

figure 26: air view of the airport

The island of Menorca, in the Mediterranean, is part of the Islas Baleares, a group of islands in spain.

Since the island is fairly big, it holds an airport and it reports, followed by the ferry boat, the main way in and out of the island. Because of its size, most of the population move around inside of the island by car.

This airport has, at its entrance, a platform with cars frequently passing both over and under it to access the main building whenever a traveler takes a plane. This will define the loads our structure will be facing.

In the meeting point of these two roads, the one going under the platform and the one going over it, there is a point at which the initial distance is much harder to bridge. The forces come into contact with the first column in an unusual pattern so this is a good spot to test the theories developed in this project. Here, codes that worked normally will have trouble keeping up

Due to the irregular shape and the stress it will suffer from it we get a perfect example for our study case.

figure 27: close-up air view

Figure 28: View of the span (section 3)

This is the distance the platform needed to skip over to connect the platform with the wall that signifies its end. Just by taking into account the side opposite to the column and how big the load it can take we lose sight of problems like the focusing of efforts on a single column or how those don't align with the reinforcement.

These issues will be analyzed in the following analysis.

Figure 29: front view of the study column

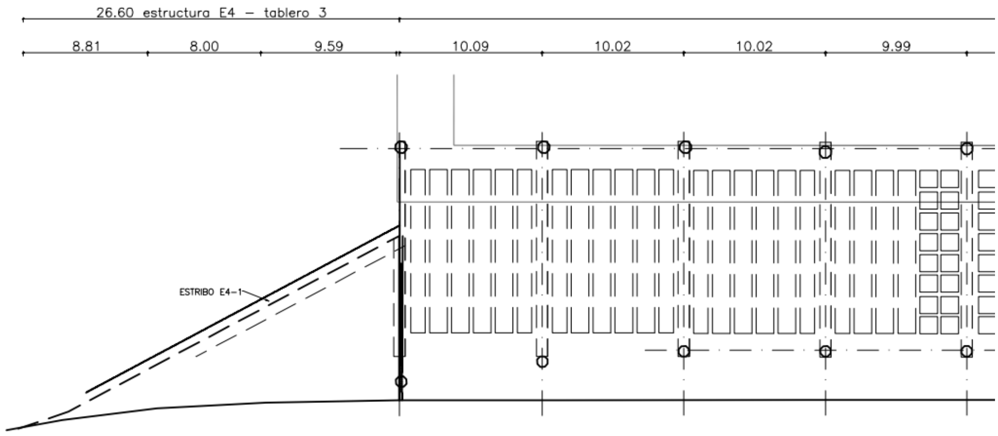


figure 30: up view of the platform

This is a closer detail of the measurements of the area and the distribution of structure and footing. As we can see here it has a different shape on each side of the column and a different distribution for both the x-axis (length) and y-axis(width) named along the sense of circulation.

It can be appreciated that the platform displays a pretty distinct behavior when regarding the way E-4' platform 3 and platform 2 behave. A dilatation joint separates them, it can be assumed that neither momentum nor shear load transfers from one side to the other. This hypothesis follows the thought process that by having the lightened slab have the alleviations align against the dilatation joint, there would be no reasonable way to transfer the effort.

On a second note, by having a platform resisting simple flexion efforts the design of the reinforcement is much easier than we would have if it were to be connected.

On top of that, it's unlikely and impractical to consider that on the top corner of platform three (triangle) on that same point, platform two can find any purchase. This is because it would transfer the shear as such:

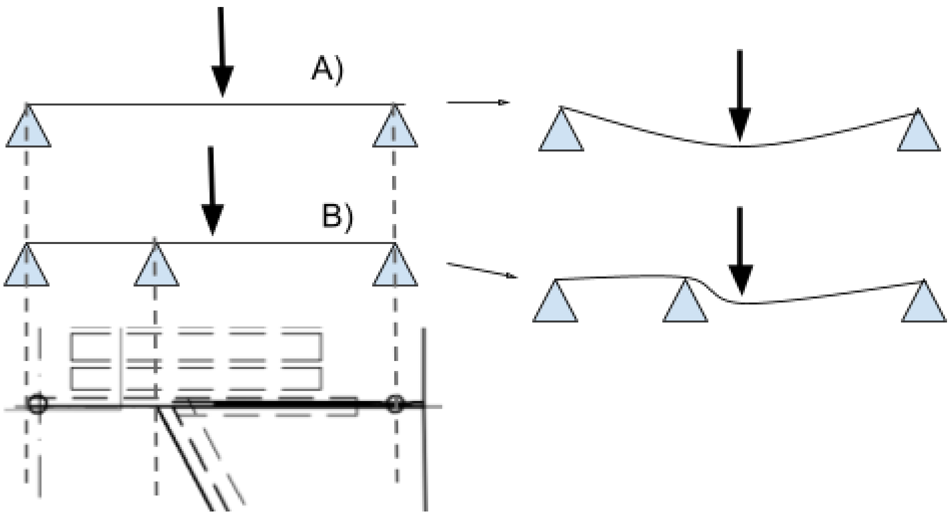


figure 31: platform descent hypothesis y-axis

This is, of course, because not only would that cause oblique efforts along platform two but also because the design of the reinforcement would become way more complicated. This would be discarded because as we said both platforms are not structurally connected and so the platform doesn't transfer forces from one side to the other. The two behaviors would have been too complicated to unify, execute and calculate in design. For this, the working hypothesis is the first. Theorizing the two slabs act as independent and between them there isn't a force transfer.

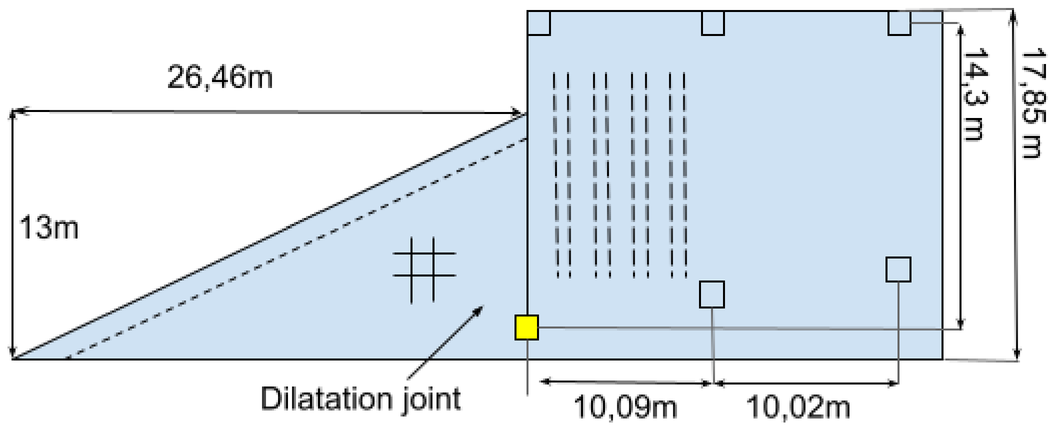


figure 32: detail of the platform

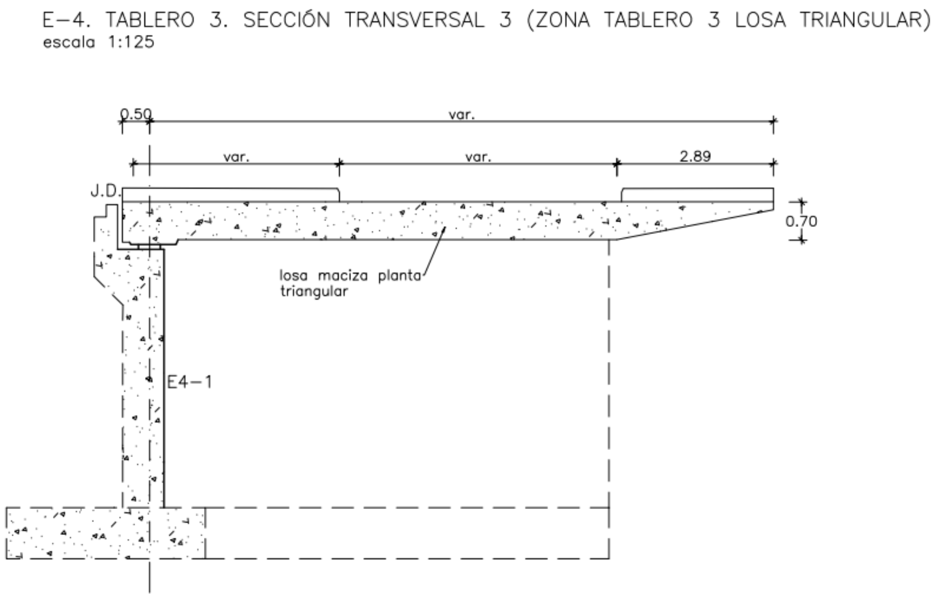


figure 33: through section of the platform (section 3) above our study column(y-axis)

The body shown in the figure is that of the platform on the triangular part, on the left and because it's triangular it doesn't have a singular width nor dimensions for most of its elements. The working theory is that its span is twelve meters. Its a solid slab of reinforced concrete so it behaves

The tests on it state that:

- It's comprised of symmetrical reinforcement B500

- On the x-axis ϕ20.25 with a coverage of 55mm
- On the y-axis ϕ20.15 with a coverage of 25mm

- The concrete has a resistance of

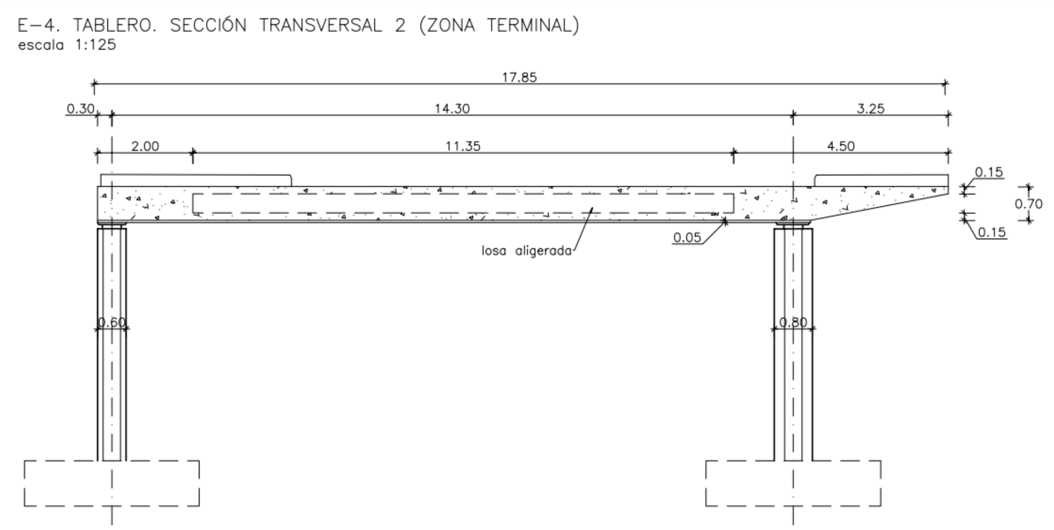


figure 34: through section of the platform (section 2) above our study column (y-axis)

On the y axis of the platform, and according to the first hypothesis, it's been represented here the weight distribution, it follows the following these laws:

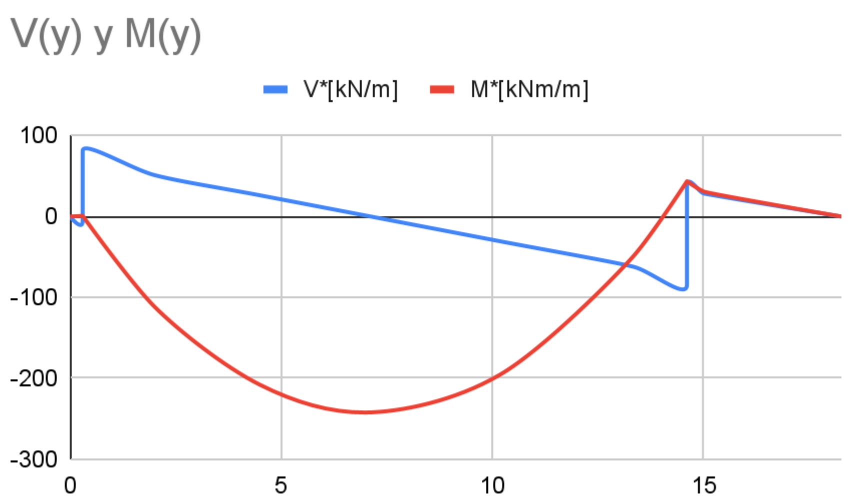


figure 35: platform loads (section 2) y-axis

The point of study is the column, located on the y=14,6m. On this graph I represented the "shear force" and the "momentum" for notice. Actually they are the shape this effort takes on that section but by themselves they do not amount to a real calculation value. This is just an example to make visual the efforts present along that axis.

As we can see, on that point, the column suffers a moderate momentum but a remarkable axile effort comparatively, 119,65 kN/m. This happens because despite it having a hanging edge that's quite long, it still acts mostly as a bi-supported beam. This is just for structural charge distribution. The passing of cars should be placed more centered but these models should help construct the kind of behavior the column will need to have.

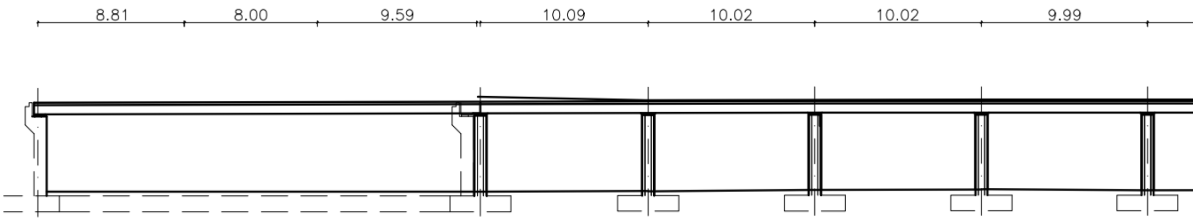


figure 36: longitudinal(x) section of the platform

In a similar fashion, efforts should behave along the x-axis. Because noticing the disconnect between platform 3 and 2 and the fact not only flexibility is much higher along the x axis but also that similar dilatation joints are set along the structure.

Using all this knowledge plus material knowledge we could get a model in SAP that would tell us in a 3D space how the loads would distribute. From using such program we get a distribution like this:

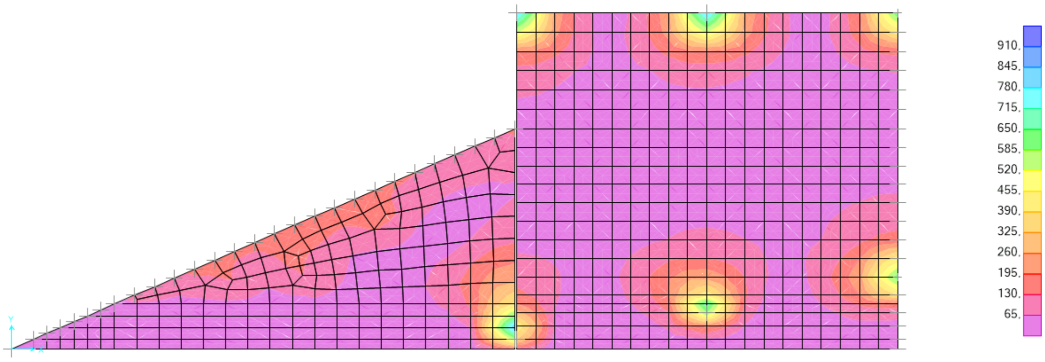


Figure 37: Shear efforts in the platform

From this we get the obvious take, that the shear effort is concentrated around the columns and that it spreads towards the other points, but most importantly we can appreciate that the discontinuity between platforms 3 and 2 is visible in the way the shear doesn't cross from one side to the other. With this model it's possible to obtain how it spreads and what are its values.

We must know now that the resistant values will need to be obtained through

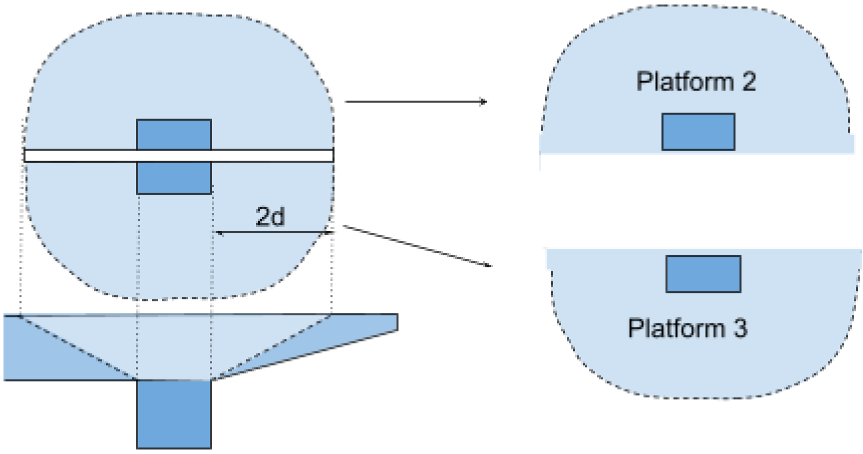


figure 38:Control perimeter of the column

According to the different codes this conundrum would be solved like this:

Eurocode2's take

$$v_{Ed} = \beta \frac{V_{Ed}}{u_1 d} \rightarrow V_{Ed,max} = (1098.31; 1170.77)\ kN$$

- $d_{eff} = \frac{(d_y + d_z)}{2} = \frac{0.675+0.645}{2} = 0.66\ m$
- $\beta = 1 + 1.8\sqrt{(\frac{e_y}{b_z})^2 + (\frac{e_z}{b_y})^2} = (1.1569; 1.0853)$
  - $e_x = \frac{M_{Ed,x}}{V_{Ed}} = (\frac{55{,}8\ kNm}{418{,}49\ kN}; \frac{78{,}66\ kNm}{783{,}2\ kN}) = (0,1333; 0,1004)\ m$
  - $e_y = \frac{M_{Ed,y}}{V_{Ed}} = (\frac{49{,}68\ kNm}{418{,}49\ kN}; \frac{44{,}41\ kNm}{783{,}2\ kN}) = (0,1187; 0,0567)\ m$
- $u_1 = 5,7469\ m$
- $v_{Rd,c} = C_{Rd,c} k(100\rho_1 f_{ck})^{1/3} + k_1\sigma_{cp} \geq v_{min} + k_1\sigma_{cp} \rightarrow 0.335\ N/mm^2$
  - $k = 1 + \sqrt{\frac{200}{d}} \leq 2\ [d\ in\ mm] \rightarrow k = 1.5505$
  - $\rho_l = \sqrt{\rho_{ly} * \rho_{lz}} \leq 0,02 \rightarrow \rho_l = 0.002317$
    - $\rho_x \rightarrow \phi 20/25 \rightarrow 1.795E - 3$
    - $\rho_y \rightarrow \phi 20/15 \rightarrow 2.992E - 3$
- $C_{Rd,c} = 0,18/\gamma_c = 0.0741$
- $v_{min} = 0,035 k^{3/2} f_{ck}^{1/2} = 0.335 N/mm^2$

- $k_1 = 0.1$ These last three are values recommended values, there are specific national annexes that contain more specific values

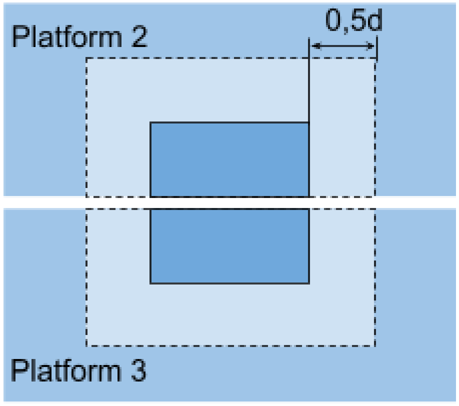


figure 39: simplification

Fib model code's take

First on the adapting of force:

$V_{Ed} = v_{perp,d,max} * b_0$

- $b_0 = k_e * b_{1,red} = (2,1865; 2,3830)\ m$
  - $k_e = \frac{1}{1+\frac{e_u}{b_u}} = (0,7672; 0,8362)\ m$
    - $e_u = \sqrt{e_x^2 + e_y^2} = (0,1785; 0,1153)\ m$
      $e_x = (0,1333; 0,1004)\ m$
      - $e_x = (0,1187; 0,0567)\ m$
    - $b_u = 0,5684\ m$
  - $b_{1,red} = 2,85$
- $v_{perp,d,max}$ is a way of mentioning the resistance but calculated per section [kN/m] to be applied on the whole contour as if it were a section of its own right. Which is the same as calculating with the shear formula but using this b as our b_0
- $V_{Rd} = V_{Rd,c} + V_{Rd,s}$ (formula 7.3-60)
- $V_{Rd,c} = k_\psi * \frac{\sqrt{f_{ck}}}{\gamma_c} * b_0 * d_v = (122.717; 133,7455)\ kN$
  - $k_\psi = \frac{1}{1.5+0.9k_{dg}\psi d} \leq 0.6$ Since we assume the structure can rotate almost freely on that point we can assume the bending has minimum effect on the resistance.
  -

- $V_{Rd,s} = \sum A_{sw} k_e \sigma_{swd}$
    - $\sigma_{swd} = \frac{E_s \psi}{6} (1 + \frac{f_{bd}}{f_{ywd}} * \frac{d}{\varphi_w}) \leq f_{ywd}$
        - φ_w
        - We can us $f_{bd} = 3MPa$

EHE's take

$\tau_{sd} \leq \tau_{rd}$

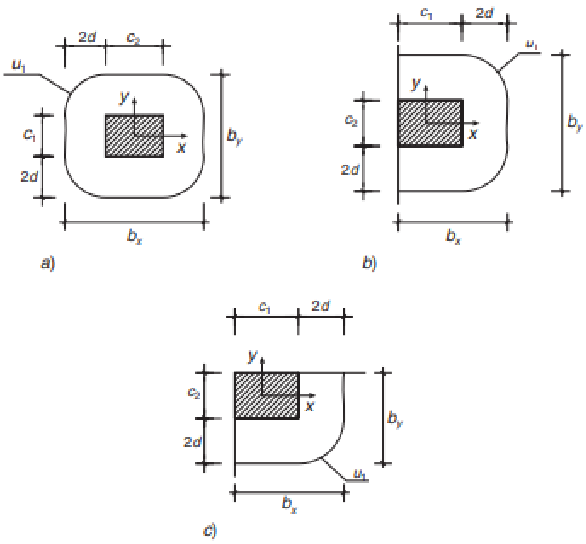
- $\tau_{sd} = \frac{F_{sd,ef}}{u_1 d} \rightarrow F_{sd,ef,max} = 55.694\ kN$
    - $F_{sd,ef} = \beta F_{sd} \rightarrow F_{sd,max} = 36.9244\ kN$
        - $\beta = 1,4$ if the charge is located at an edge
    - $u_1 = 5.9982\ m$
    - 

figure 40: Critical surface (EHE figures 46.2.a,b&c)

- $d = 0.66$ refers to the effective thickness=0.675m
- $\tau_{rd} = \frac{0,18}{\gamma_c} \xi (100 \rho_l f_{cv})^{1/3} + 0,1\sigma'_{cd} \geq \frac{0,075}{\gamma_c} \xi^{3/2} f_{cv}^{1/2} + 0,1\sigma'_{cd} \rightarrow \tau_{rd} = 13.058\ kN/m^2$
    - $\xi = 1 + \sqrt{\frac{200}{d}} \leq 2 \rightarrow \xi = 1.5443$

- $\gamma_c = 1.35$
- $\rho_l = \sqrt{\rho_x \rho_y} \leq 0,02 \rightarrow \rho_l = 0.002317$
  - $\rho_x \rightarrow \phi 20/25 \rightarrow 1.795E - 3$
  - $\rho_y \rightarrow \phi 20/15 \rightarrow 2.992E - 3$
- $f_{cv} = f_{ck} < 15N/mm^2 \rightarrow f_{cv} = 15N/mm^2$
- $\sigma'_{cd} = 0$

Code \ Shear resistance	Platform 3	Platform 2
Eurocode	1098.31	1170.77
Fib model code	122.74	133,745
EHE	36.94	36,94
Modelization efforts:	418.49	783.2

From the results here observed we can see how these columns are in high risk of suffering from shear failure. Analyzing the structure one can guess there's more resistant mechanisms than the plans show for if this were to be all there is then the structure would have long failed by now.

This structure barely shows any cracks on the study area, which goes to prove the aforementioned theory.

7. Conclusion

The first difference one can appreciate when looking at the differences between the codes is that the Eurocode and the EHE have similar approaches for the size of the control perimeter whereas the fib model code doesn't. The first two take a spreading of $cotg\theta = 2$ for the crack, which is quite high when calculating general shear resistance but might be reasonable if we consider the resistant mechanism to be limited on most fronts. On the other hand, the fib model code takes a $cotg\theta = 0,5$, quite low even under normal circumstances.

This doesn't affect greatly the calculations of the experiment since the reinforcement is close enough it will be reached anyways. But in a normal situation this doesn't happen. There will be a great variation depending on how the reinforcement is distributed because the amount taken into the resistant lot will change accordingly.

There is also a particular issue I have with the experiment. By placing the reinforcements we called ϕz t way they did. They manage to assure the tension inside the reinforcement is measured. But they lose perspective of one of the dangers of reinforcement, pull-out. By placing it this way it becomes impossible for the reinforcement to suffer pull-out failure which otherwise it would have.

But overall this analysis tells us the fib's approach, with its combination of both the actions of concrete and steel should provide better results, in the sense that they are closer to the practical values consistently. Mind it that a piece heavy on the reinforcement or on the concrete load should still show good results but for efficiency's sake, it kind of leads you towards choosing a main route and having the other more as a backup measure than an actual central axis of resistance.

This method gives designers and anyone in charge of checking the resistance of the element a faster path to it. Mind that this will probably end up being a small piece in a bigger set, so speed can be an important value to take into account. As more of the calculations become automatized I would recommend a joined calculation of forces.

Maybe the value taken to calculate the concrete should be, not the simplification, which doesn't really make the process so much faster but the area of the crack and none of the codes take this approach.

We should also speak of the transfer between front or back rows. It's an element we can ponder pretty unproblematically in this document but when thinking of the real life implications this model and the adjustments it pursues onto the codes could turn out to have disastrous consequences towards real life designs. The procedure should be to take the value of the front row to be safe if more specific info cannot be obtained.

When working towards a definitive code, it would be expected that this transfer was specified. Mind that when working with more complicated anchor systems the importance of this nuance increases as more and more of the charge will be transferred to rows on the back.

The eurocode has grown stiff and holds way too many turns and specifics that aren't all that useful. The spanish code, really similar in approach and methods has cut out many of the possible cases so as to make the process as straightforward as possible without any danger and much higher costs. Apart from that the experience of using the EHE is much more reassuring because it feels refreshed.

If we could pick and choose these are the attributes I should see appear in a future code, since this is conceptualized as more of a contest than a build your code, I shall proclaim the fib has shown much better results on the experiments we tested it and is therefore the winner.

8. Annexes

This space was saved for calculations that took up too much space in the main body and of text but felt off not being included.

Annex I Shear area

The general assumption deals on the lines that the force spreads through the structure in a conical manner from the application point. This application point is not a singular point in space, we can assume it is in the horizontal plane but we can't do that on the vertical one.

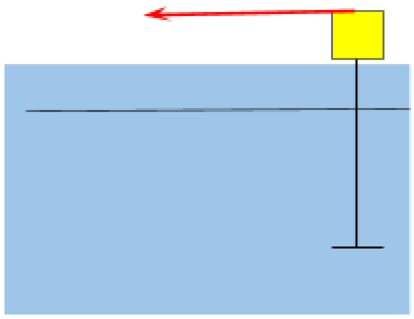


figure A1: Stirrup detail

In this close up detail of our application point we can see that the element we had previously disentangled from the idea of a singular point is in fact a line from which the force spreads.

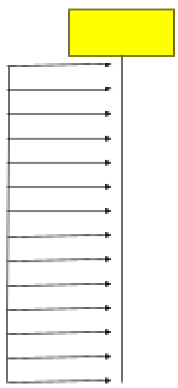


figure A2: Simplified effort distribution

The force, when transferred from the stirrup onto the concrete creates a field of compressions and tractions that resists

the force applied. On the areas where tractions are stronger the fissures begin to appear and the breakout piece takes a shape similar to a cone projected along a line perpendicular to its long axis.

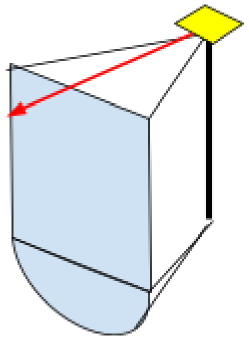


figure A3: Fissuration cone

A problem arises with this situation: the tip of the stirrup is projecting onto a much bigger piece of the structure than the rest of it. For this to happen it would mean that the resistant effort is being curved as it reaches the end as shown in figure A4.

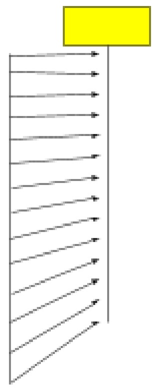


figure A4:Adapted to engrainment efforts

There is also a second set of problems with this that pile onto the former. Since this particular element’s analysis is being assimilated to an embedded beam, this means that the displacements and rotations would accumulate and thus the strength the structure can pass on to the stirrup is diminished as we wander further from the anchor.

This happens because we’re not working with gliding efforts, the way we usually study we are led to believe that forces follow along the displacements as they happen. We would make the assumption originally that

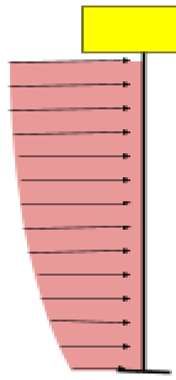


figure A5: Adapted to Flexibility efforts

Seeing as the certainty and relevance of the forces decrease as we approach the limits of influence, the simplification the fib model and the eurocode propose become easier to justify.

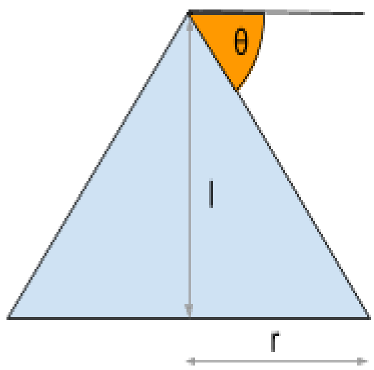
Conical model

The apparent from the experiment one, a half cone connected to a triangular prism that extends until it reaches surfaces is the one closest to what the experiments show and yet the codes put into doubt whether or not the conical part actually brings us information about the resistance.

In any case this relevance is much higher when we consider that the distance to the weak edge is much higher than the length of the single stirrup.

To calculate the parameters of this projection, it was divided into its geometrical pieces.

1. The first part is the conic piece, we know its radius grows depending on the length of its central axis because we know the angle it forms with the horizontal axis.



1.1. $l = c_1$

1.2. $r = l/tan(\theta)$

1.2.1. $\theta = 33.69º$ for the calculations in the fib and therefore those of the eurocode were assumed to be the same:

1.2.2. $tan(\theta)^{-1} \approx 1.5$

1.2.3. r$\approx l * 1.5$

1.3. Area of the semicircular base: $A = r^2 * \frac{\pi}{2} \approx 3.5l^2$

1.4. Volume of the half-cone: $V = \frac{A_{base} * l}{3} \approx 1.18l^3$

1.5. And lastly, surface of the cone:
This surface area is the area of the bottom plus the Area of this contraption, that would be the decomposition of the side of the cone. This can be modeled as a section of a circle with radius the long side of the cone and as perimeter, the half-circle that makes the half-cone's base.

1.5.1. The perimeter is obtained through the formula:
$P_{base} = 2\pi r_{base} \approx 3.46l$

1.5.2. The long side, we'll use as our new radius:

$$r_{long} = \sqrt{r_{base}^2 + l^2} \approx 1.14l$$

1.5.3. The Area of the section is thus the proportion the area encompassed by the perimeter takes compared to the ideal perimeter a circle of this radius would have multiplied by the area of that circle:

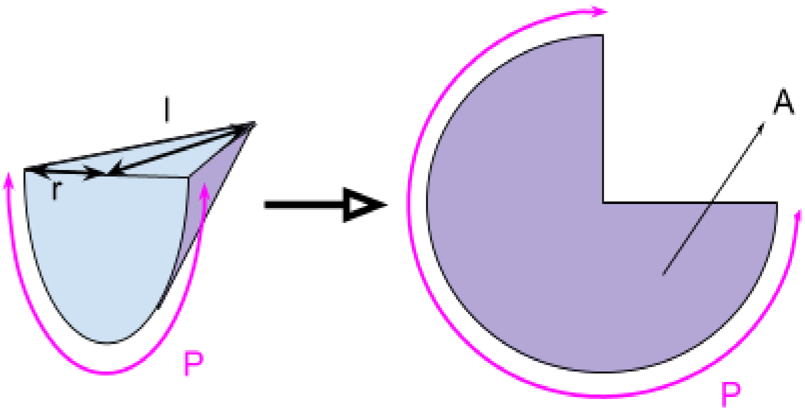


figure A6: Surface of a cone

And from this we get the following formula:

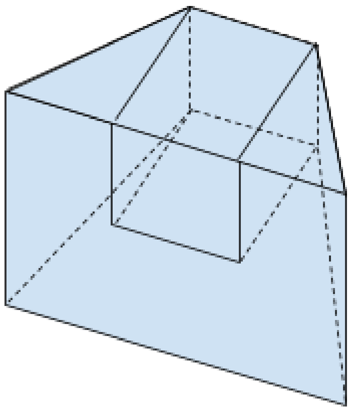
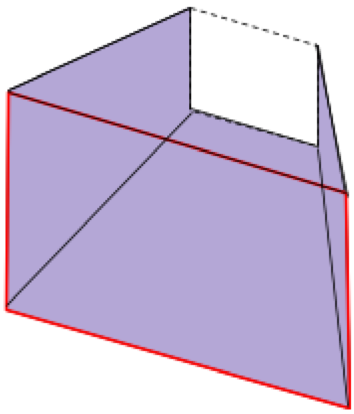
$$A_s = \frac{P_{base}}{2\pi r_{long}} \pi r_{long}^2 = \frac{P_{base} * r_{long}}{2} \approx 2l^2$$

2. The second piece is shaped like a triangular prism. It is useful to calculate it as a combination of the previous values and therefore simplify the process.
   2.1. Its rectangular base, diameter times length of the stirrup:
   $A_{base} = l_s * 2r$
   2.2. Its volume: $V = \frac{l * A_{base}}{2}$
   2.3. The surface on the sides, the surface of engrainment:
   $A_{sides} = 2 * \sqrt{l^2 + r^2} * l_s$

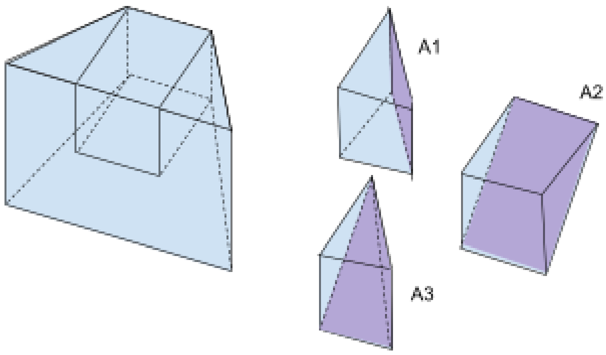
3. Thus the total engrainment surface following this model would be:
   $A_{Ext} = 2 * \sqrt{l^2 + r^2} * l_s + 2l^2$
   $A \simeq$

Pyramidal model

This other model is composed too by two pieces, a pyramid piece:that would substitute the conical one, which is complicated to work with geometrically. This abstraction needn't be done in our study but it is the approach the fib takes at a point so it's interesting to consider it.

Here we see in purple the resistant mechanism and in red the line u1 used to give a proporional value.



1. $A1 = \sqrt{(1.5h)^2 + h^2} * c2 = 1.8h * c2$
2. $A2 = \sqrt{(1.5h)^2 + h^2} * c1 = 1.8h * c1$
3. $A3 = 2 * \sqrt{(1.5h)^2 + h^2} * (1.5h)\ /2 = 2.7h^2$

$A = 2 * A1 + A2 + 2 * A3 = h * (3.6c2 + 1.8c1 + 5.4h) \rightarrow c1 \simeq c2 \simeq h/2$

$A \simeq 32.4c^2$

Anexo de Objetivos de desarrollo Sostenibles

Relación del TFG/TFM "Comparing the convenience of construction rules: fib, EHE or Eurocode 2 Applied to calculating shear resistance on oblique concrete cracks" **con los Objetivos de Desarrollo Sostenible de la Agenda 2030.**

Grado de relación del trabajo con los Objetivos de Desarrollo Sostenible (ODS).

Objetivos de Desarrollo Sostenibles	Alto	Medio	Bajo	No Procede
ODS 1. Fin de la pobreza.				X
ODS 2. Hambre cero.				X
ODS 3. Salud y bienestar.			X	
ODS 4. Educación de calidad.		X		
ODS 5. Igualdad de género.				X
ODS 6. Agua limpia y saneamiento.				X
ODS 7. Energía asequible y no contaminante.				X
ODS 8. Trabajo decente y crecimiento económico.		X		
ODS 9. Industria, innovación e infraestructuras.	X			
ODS 10. Reducción de las desigualdades.			X	
ODS 11. Ciudades y comunidades sostenibles.		X		
ODS 12. Producción y consumo responsables.		X		

ODS 13. **Acción por el clima.**			X	
ODS 14. **Vida submarina.**				X
ODS 15. **Vida de ecosistemas terrestres.**				X
ODS 16. **Paz, justicia e instituciones sólidas.**	X			
ODS 17. **Alianzas para lograr objetivos.**	X			

Descripción de la alineación del TFG con los ODS con un grado de relación más alto:

This project is an international collaboration between experts from different countries. It searches to strengthen the codes and laws by which we assure our structures will behave properly in the future.

I would say its forte lies on ODS16 and ODS17 This is the product of three different organizations from three different countries. United together with the hopes of making those institutions, the codes, stronger, fairer and more widely accepted.

By improving the laws governing us we are making the alliance the European union represents and the institution itself sturdier. Arming its citizens with more useful tools, and fairly anyone willing to trust the codes, we are improving the trust we lay on it.

This also has its effects on ODS9 since it improves the efficiency of the construction industry. Knowing how much we can safely save from a structure's production costs, be it economic or ecological, will be an improvement affecting industry. Apart from that, this same growth will have its effects on ODS8, ODS11 and ODS12 making progress, step by step more responsible for the same future it bolsters.

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