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ProtaStructure Design Guide

Column Punching Shear Checks to BS8110 and EuroCode 2

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Table of Contents

Column Punching Shear Checks

Introduction

The nature of the design code requirements tend to dictate that punching shear checks cannot be safely & fully automated in batch runs. For this reason, ProtaStructure's punching shear check is an interactive design tool, you need to use it carefully on one column, or a group of similar column(s) at a time to review/establish the correct design settings. Having done so rechecking can be carried out in a more automatic fashion.

In this document, we will show what this check can do for you for BS8110 & EuroCode 2. We will also illustrate the limitations of which you need to be aware.

BS8110 Design Code Requirements

The Design Procedure

In **BS8110 section 3.7.6** covers the requirements for checking punching shear. Protostructure's punching shear check cannot be used without a reasonable understanding of the code's requirements. The following notes provide a brief overview of these; then in the next section we will use specific examples to go into more detail and illustrate limitations.

BS8110 cl 3.7.7.6 describes a design procedure; the notes below expand on this.

Check Maximum Shear Capacity

This is a check at the face of the loaded area, refer to **BS8110 cl 3.7.6.4.**

By default, Protostructures will perform this check, but limitations do apply.

Check Shear on Series of Perimeters

The first perimeter is at 1.5d from the face of the column (the loaded area) subsequent perimeters are at 0.75d increments – *i.e. 2.25d, 3.00d, 3.75d, etc.*

To make an accurate check on each perimeter the following needs to be known/controlled:

- Is it an internal/edge/corner condition?
- How much main reinforcement is effective?
- Are there holes, for which you need to account?

For each perimeter three results are possible:

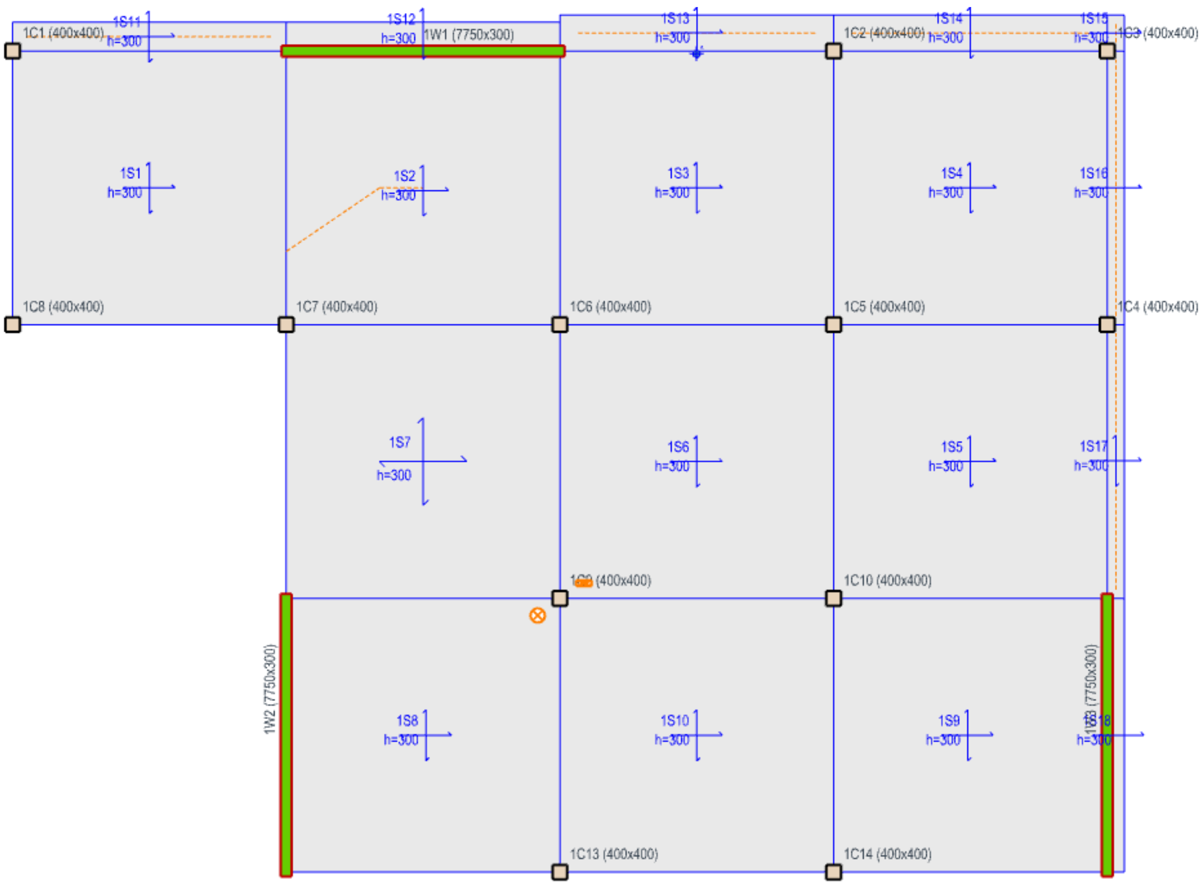
- The check fails with $v > 2v_c$ in which case a required area of shear reinforcement cannot be calculated so the whole checking procedure terminates.
- The check fails but the required area of shear reinforcement can be calculated, and the checking procedure moves on to the next check perimeter.

- The check passes – in which case no shear reinforcement is required and no further checks on subsequent perimeters are required.

Where shear reinforcement is found to be required on a Check Perimeter it is important to note that it is then provided on (and shared between) two reinforcing perimeters as discussed later.

Simple BS 8110 Examples

In this section we will look at a series of relatively simple BS8110 examples using the model shown below.

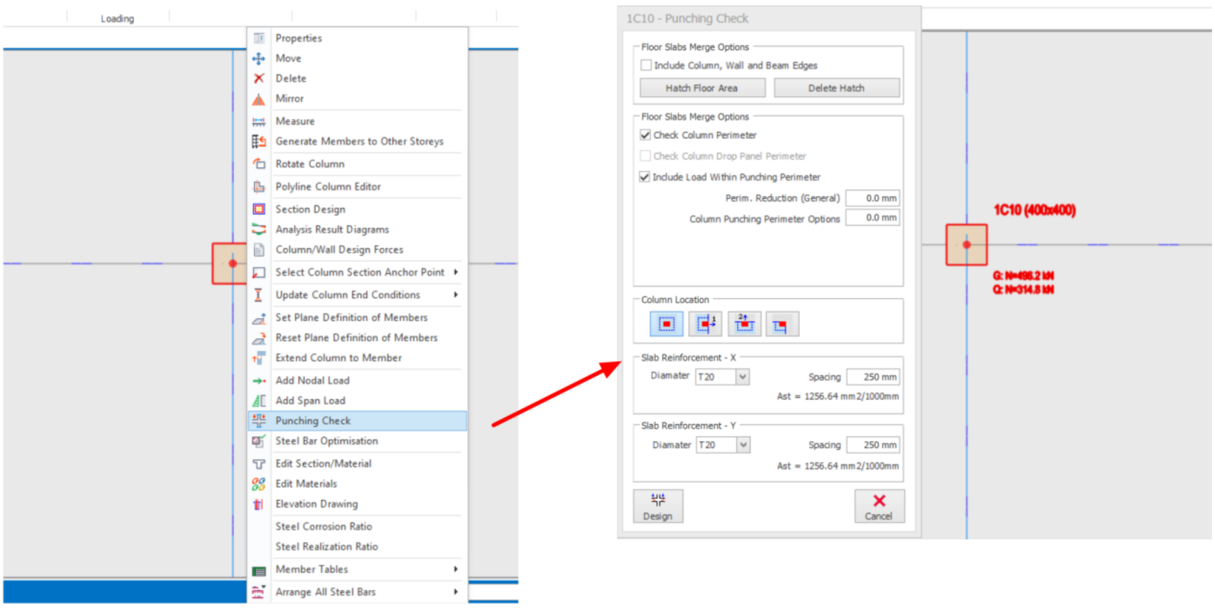


This simple model is sufficient to illustrate most aspects of the checking procedure including:

- A typical internal column.
- Typical edge columns with varying slab cantilevers.
- Typical corner columns with varying slab cantilevers.
- The effects of openings.

The model is set out on a regular 7.5 m grid, the slab is 300 thick with 0.5 kN/m2 finishes and 5.0 kN/m2 imposed load. The columns are 400 mm square.

Checking a Typical Internal Column



Performing the Check

In the figure above, column 1C10 is selected, right click and select the *Column Punching Check* option to call out the punching check dialog as shown. The options this exposes will generally be discussed in more detail as we go through the examples, but in summary they are:

Floor Slab Merging Options

- These options would be used in cases where the punching perimeters are not found (generally in cases of complex slab geometry), refer to the section ***Slab Merging*** for more details. In the first instance these options can be ignored.

Column Punching Perimeter Options

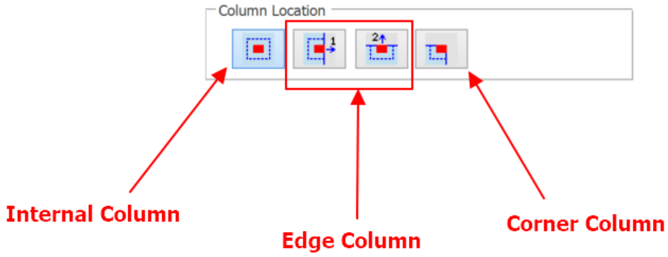
For circular columns, the same principle applies - BS8110 only considers idealised rectangular perimeters so checks should be made using the rectangular as opposed to the circular setting.

- Check Column Perimeter and Check Column Drop Panel Perimeter *(only active if a drop has been defined)* – These options allow the check on maximum shear capacity at the face of the loaded area to be toggled on and off.
- Periphery Reduction Amount – An allowance for holes that have not been modelled or may be cut in the future – see the section on Dealing with Openings.
- Include Load Within Punching Perimeter – When this option is checked, the shear load considered on each successive punching perimeters will reduce (due to the increasing area of loading that falls within the punching perimeter). When un-checked the shear load will be the same on all perimeters – *i.e. the check becomes more conservative.*

Column Location

- In this field, users have to pick the location of the column in flat slabs (internal/ edge/corner) to determine the equation for shear checks as detailed in BS8110 cl 3.7.6.2 and 3.7.6.3.

- Figure below shows the location of the column represented by each symbol.



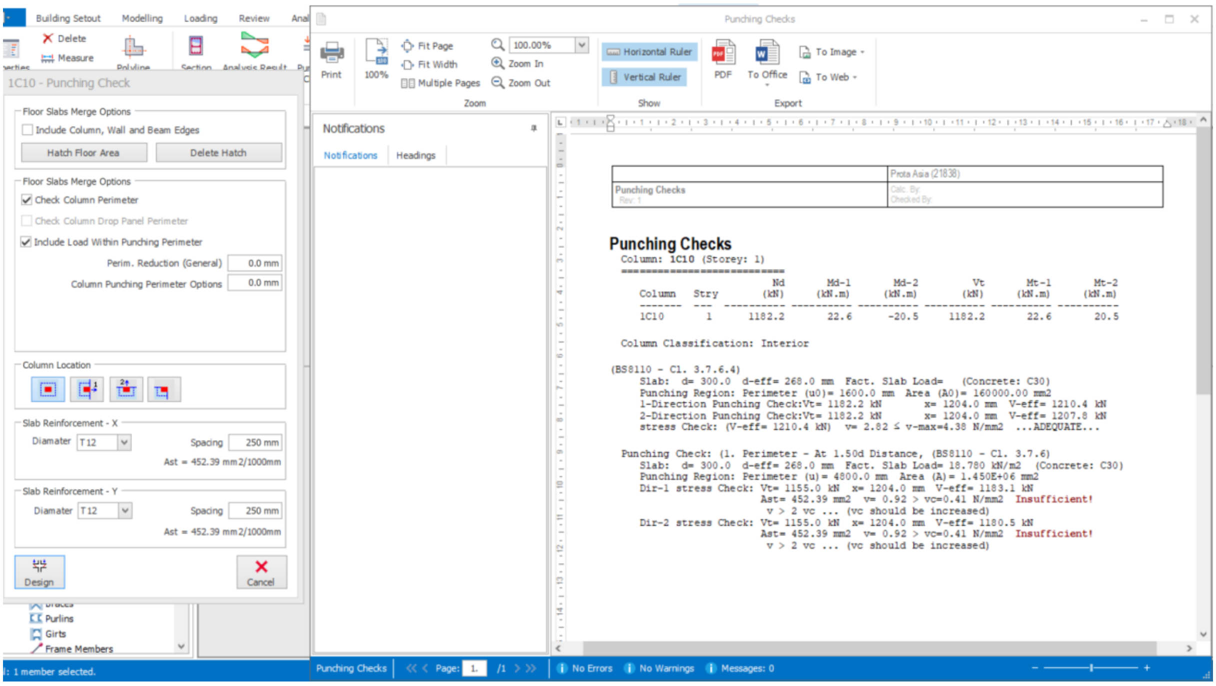
Slab Reinforcement X (and Y)

- Diameter of slab reinforcement and spacing must be input in this field to obtain the provided reinforcement, A_{st}.

Checking Maximum Shear Capacity

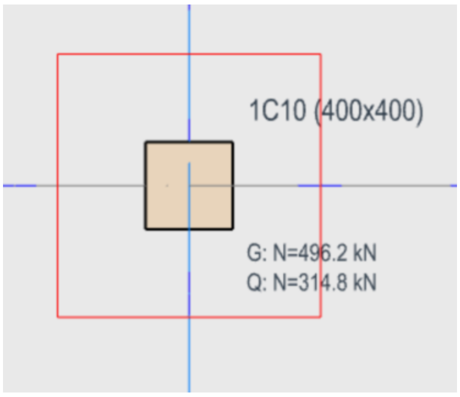
This is a check at the face of the column (loaded area), refer to **BS8110 cl 3.7.6.4.**

If no changes are made and the column is checked with the settings as shown in the figure below, the result will be generated and shown in another window.



The output indicates the design forces and then makes the first punching check (at the face of the loaded area) and second punching check (which 1.5d distance away from the face of the column). The first punching check was passed but second punching check was failed.

As shown in the figure below, the red perimeter around the column is indicating that the punching checks is failed when the perimeter was 1.50d distance away from the face of the column.

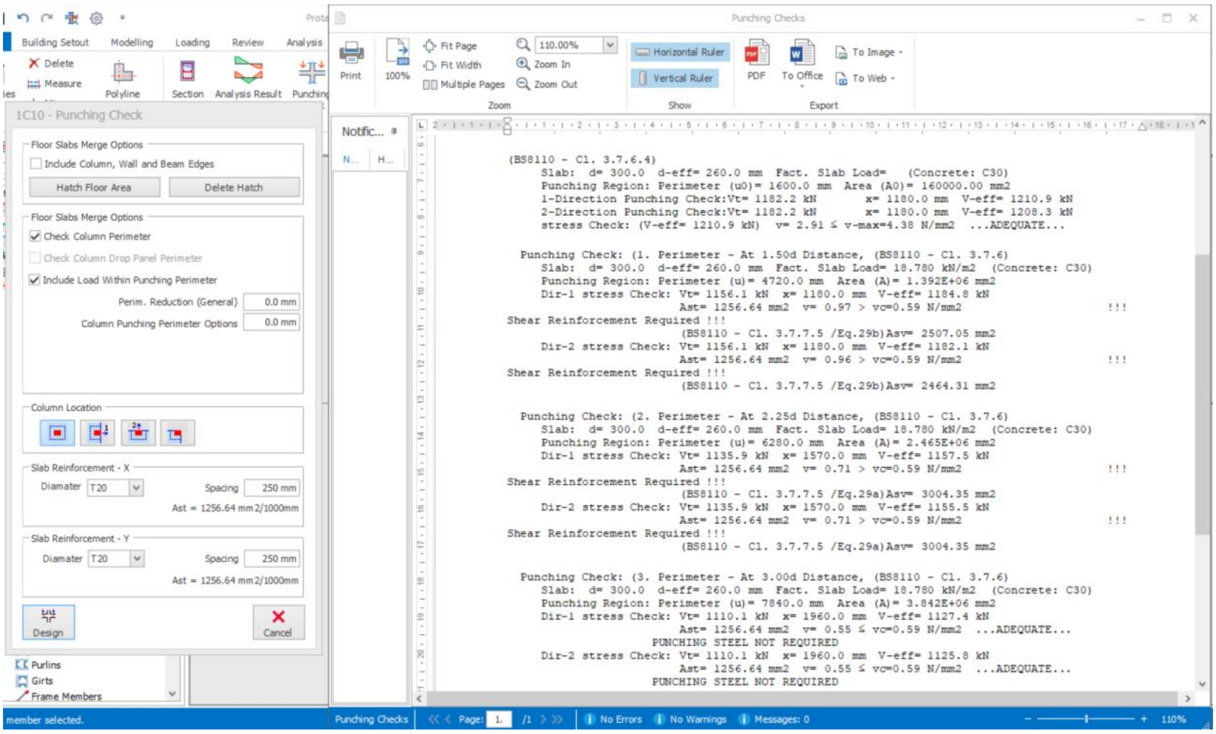


Check Shear on a Series of Perimeters

Continuing with the same example, the **BS 8110 cl. 3.7.7.4** requires the first perimeter check to be made at 1.5 d from the face of the column (the loaded area). Note that V_t is slightly reduced for this perimeter, from 1162.2 kN at the face of the column to 1154.9 kN (because the option to include the load within the punching perimeter is checked).

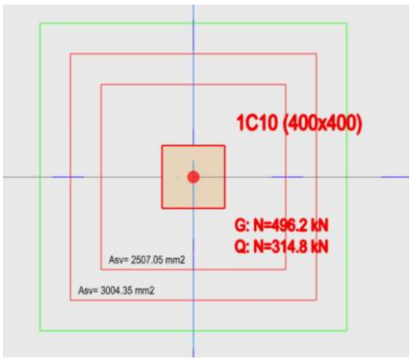
The output above indicates that $v > 2v_c$ – reference should be made to **BS8110 cl 3.7.7.5**, once v exceeds this level justification of shear resistance moves beyond the limits of the code. Hence in this situation ProtaStructure simply indicates the perimeter in red on the plan view and the output suggests that something must be done to increase v_c (or reduce v).

The shear capacity v_c is influenced by concrete grade and provided steel. For the first punching shear check, the bars T12@250mm was set. Clearly, a much higher steel provision would be normal across a column head, so we can now rerun the check with more realistic steel – say T20@250mm.



The result for this revised check is shown in the figure above.

- The 1st perimeter at **1.5d** is checked and it fails, and A_{sv} required is determined as 2507.05 mm^2.
- The 2nd perimeter at **2.25d** is checked and it fails, and A_{sv} required is determined as 3004.35 mm^2.
- The 3rd perimeter at **3.00d** is checked and it passes – so no further perimeters need to be checked.



The figure above is showing the plan view reflects these key results:

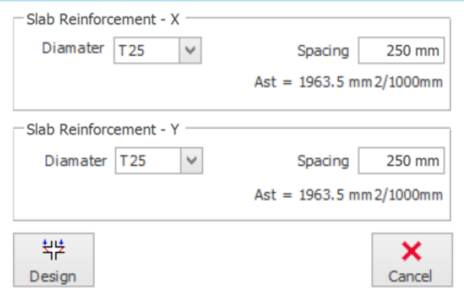
- The first two perimeters are shown red and the A_{sv} requirement is written on each perimeter.
- The 3rd perimeter is green. This sort of red, red, green series of perimeters is ultimately what you will see on all of the columns.

Since the punching shear perimeter length increases and the shear load decreases on each successive perimeter, you may expect to see a reducing Asv requirement on the successive perimeters. For higher shear loads this will be true, however, where nominal shear reinforcement is required (Asv min = $0.4ud/0.95f_{yv}$) the requirement will increase as a function of perimeter length (u).

<u>**The input of shear reinforcement has 2 effects:**</u>

- The bar size influences the value of effective depth (d) used in the checks.
- The spacing affect the total effective tension steel (A_{st}).

In practice, you might actually have alternate bars of different sizes providing a total A_{st} (say 1850 mm^2/m for the purposes of an example). In this case, you would simply use the larger bar size and adjust the spacing to achieve the correct A_{st} value as shown below. The A_{st} value is governing the punching shear check, the spacing is irrelevant in the context of this check.



Providing Shear Reinforcement

ProtaStructure will create a plan view showing all the failed perimeters and the associated A_{sv} requirements.

Note that on 1C5 the very slightly higher punching load is sufficient to mean that the A_{sv} requirement on the first perimeter is greater than the minimum requirement which applies on 1C6. However, the minimum requirement applies to both columns on the second perimeter.

In practice, punching shear resistance may be provided in different ways using various proprietary systems. If it is to be provided using links, the detailing requirements of ***BS8110 cl 3.7.7.6*** and ***figure 3.17*** must be adhered to. This remains a detailing exercise, but the following notes indicate the points to watch – continue to consider column 1C6:

<u>Check Perimeter at 1.5d:</u>

The 2258.05 mm^2 required at the first check perimeter should be provided on at least 2 reinforcement perimeters:

- At **0.5d** – at least 40% i.e. approx. 903 mm^2
- At **1.25d** – the balance of approx. 1355 mm^2

<u>Check Perimeter at 2.25d:</u>

The 3004.35 mm^2 at this second check perimeter must again be provided on 2 reinforcement perimeters the first of which is at 1.25d and is therefore common to the previous check perimeter.

- At **1.25d** – at least 40% i.e. approx. 1202 mm^2 – but 1355 mm^2 already provided above.
- At **2.0d** – the balance of approx. 1803 mm^2 but 1803 mm^2– 1355 mm^2 (provided above) = **448 mm^2 is required.**

Now considering the detailing requirements on each perimeter. The main restriction to take note is that the maximum spacing of link legs along any perimeter is 1.5d which in this example is a spacing of 380 mm. The spacing of main bars is likely to further dictate the maximum spacing that can be used – say main bars are at 100 crs then maximum reasonable spacing is 300 mm. The table below indicates the minimum area of shear reinforcement that will be provided on each perimeter if a 300 mm link leg spacing is used.

Perimeter at (distance from face of column)	Min. Asv req'd mm^2	Perimeter Length	Min No of Link Legs (at 300 mm crs)	Min Area of shear reinforcement provided assuming min bar size of, mm^2			
				T8	T10	T12	T16
0.5d	903	2640	9	452	707	1018	1810
1.25d	1355	4200	14	704	1100	1583	2815
2d	448	5760	20	1005	1492	2149	3820

It seems that T12 legs at 300 will be required on each of 3 reinforcing perimeters.

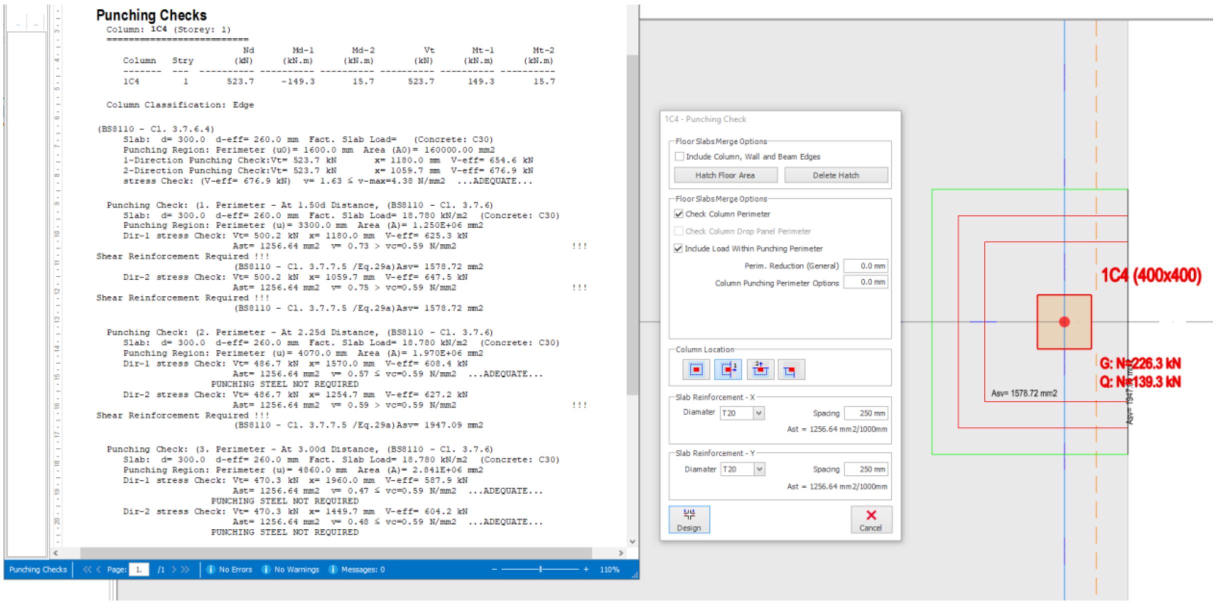
There are some further points to consider in relation to the provision of shear reinforcement around holes. See further comments in the section ***Dealing with Openings.***

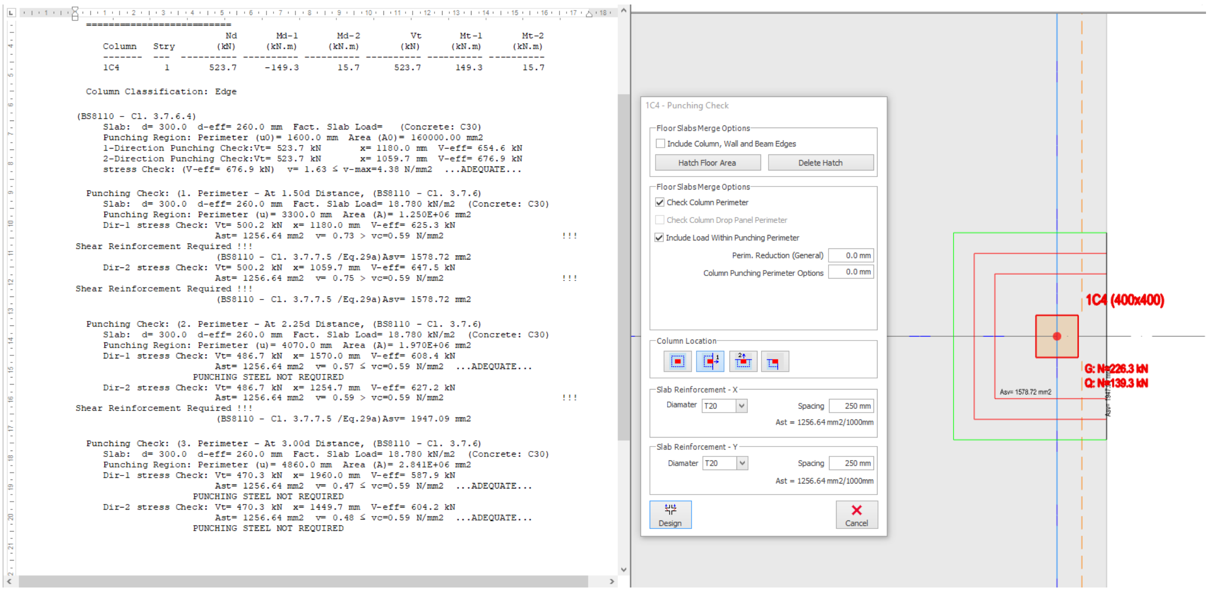
Checking a Typical Edge Column

In the figure above, a column close to an edge has been selected and a check has been made using the same settings as were used for the internal columns above.

The figure shows how ProtaStructure has correctly detected the shortest punching perimeter in accordance with **BS8110 figure 3.19**, however, **clauses 3.7.6.2** and **3.7.6.3** require that a distinction be made between internal and edge columns. This affects the calculation of V_{eff} in both directions. ProtaStructure cannot make this distinction automatically for all possible geometries, and so it never attempts to make it at all. Users must always control this selection.

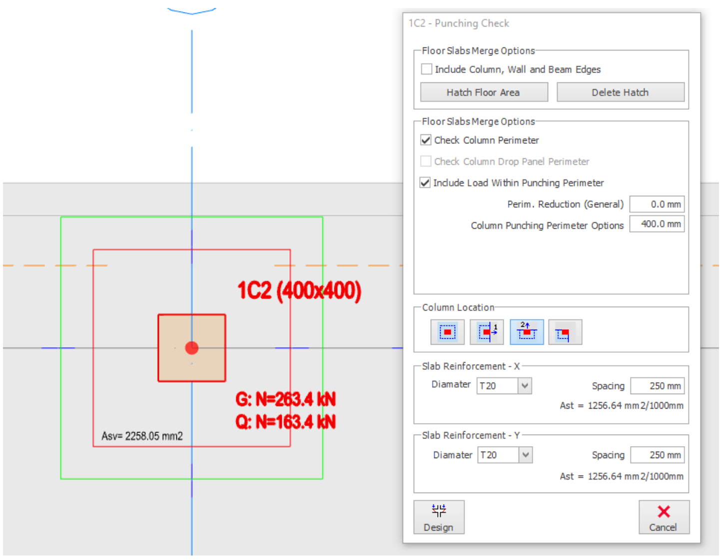
In this simple case, the red and green perimeters clearly indicate that the free edge is close enough that this check should be made as an edge condition on all perimeters. If we rerun the check after changing to the appropriate column location setting the result changes as shown below.



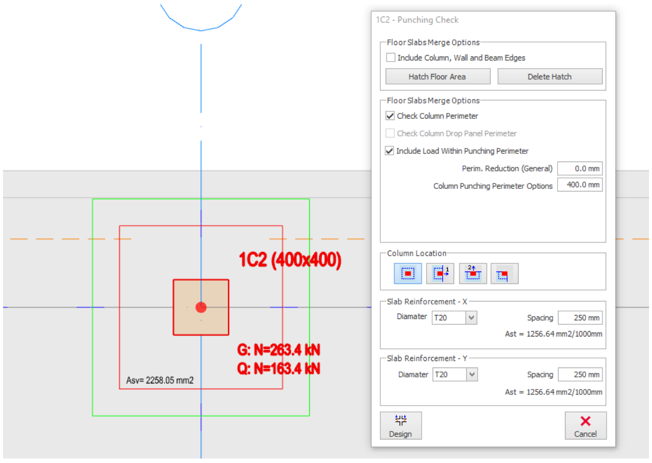


The result looks similar, but the A_{sv} requirements have actually changed. In fact, in this example the requirement on the first perimeter has reduced, and on the second perimeter min requirements continue to apply. In fact, because of the way ProtaStructure calculates the dimension x used in the calculation of V_{eff} (see later discussion) this is likely to be the case, but this result cannot be guaranteed for all edge conditions.

As an example of where some care needs to be taken with the selection of edge conditions, consider the column shown below.

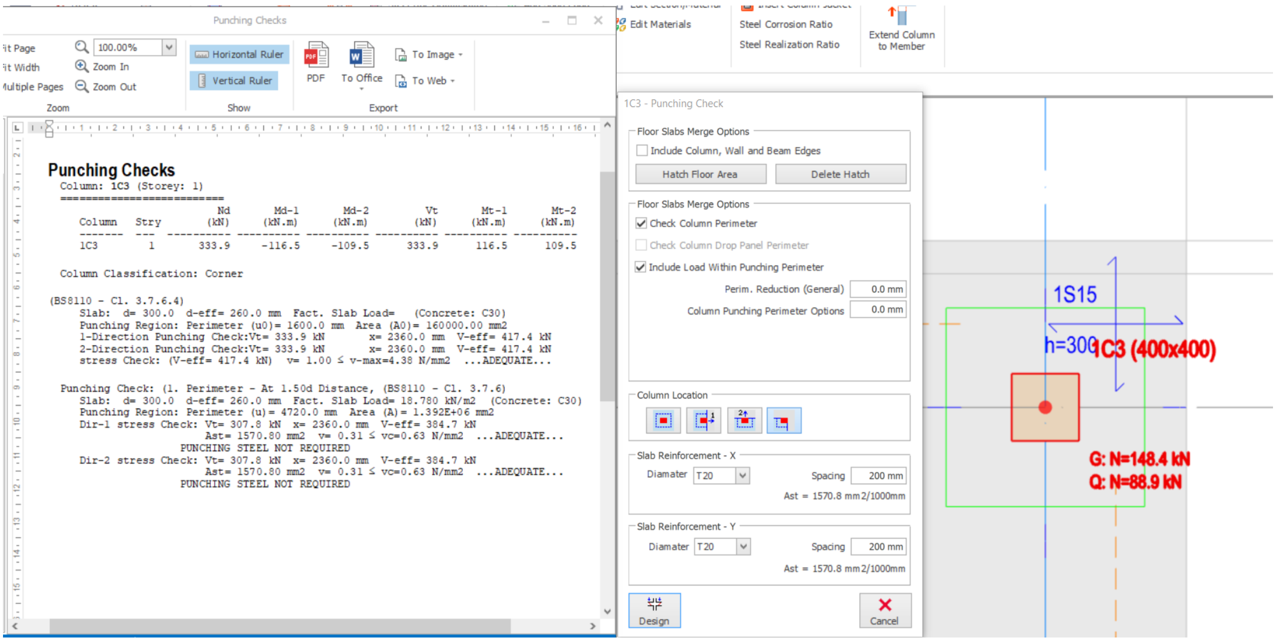


The first perimeter is that of an internal column, the second is an edge condition. When checked as an internal column the A_{sv} requirement shown above is 2258.05 mm^2 (min reinforcement). When checked as an edge column the calculation of v changes, but the minimum A_{sv} requirement continues to apply – *i.e. the result is unchanged in this example.*



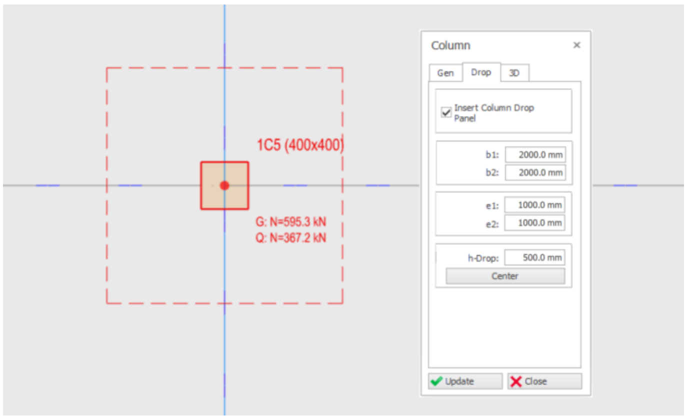
The figure above shows the A_{sv} when the column checked as internal column is the same when the column checked as edge column. Beyond the requirement to consider and apply the appropriate check there is no difference between the checks for internal and edge columns.

Checking a Typical Corner Column



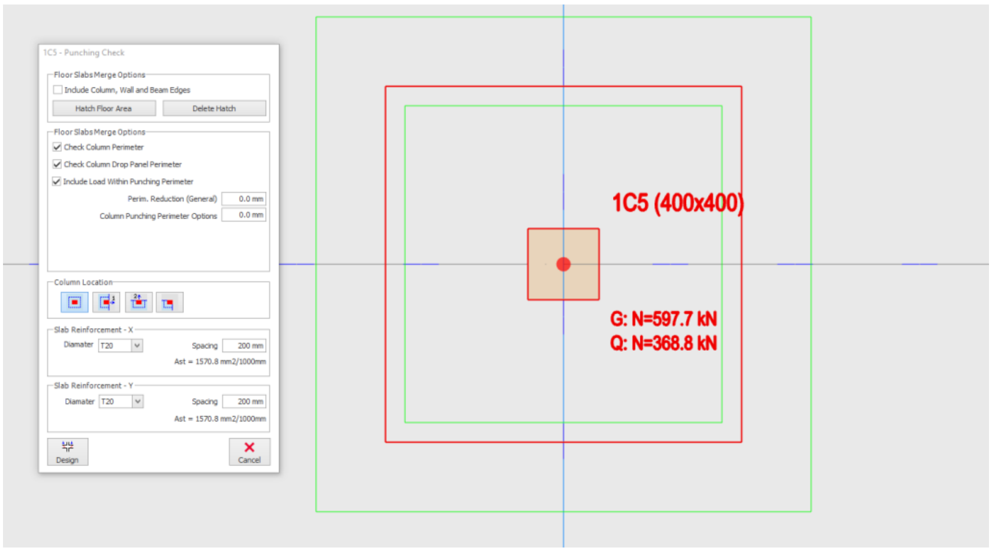
The example shown above illustrates a simple corner column case. The points made for the edge column in the previous section are equally applicable here, the obvious difference being that the corner column location must be selected. In this example, the corner column with significant overhangs passes the punching shear check with no reinforcement being required.

Column Drop Panels



As shown in the figure above, column 1C5 has been selected and a 2m square by 500mm deep drop panel has been defined at the top of the column.

The purpose of a drop panel is typically to remove the need for additional punching shear reinforcement. This can be achieved by adjusting the geometry of the column drop panel.

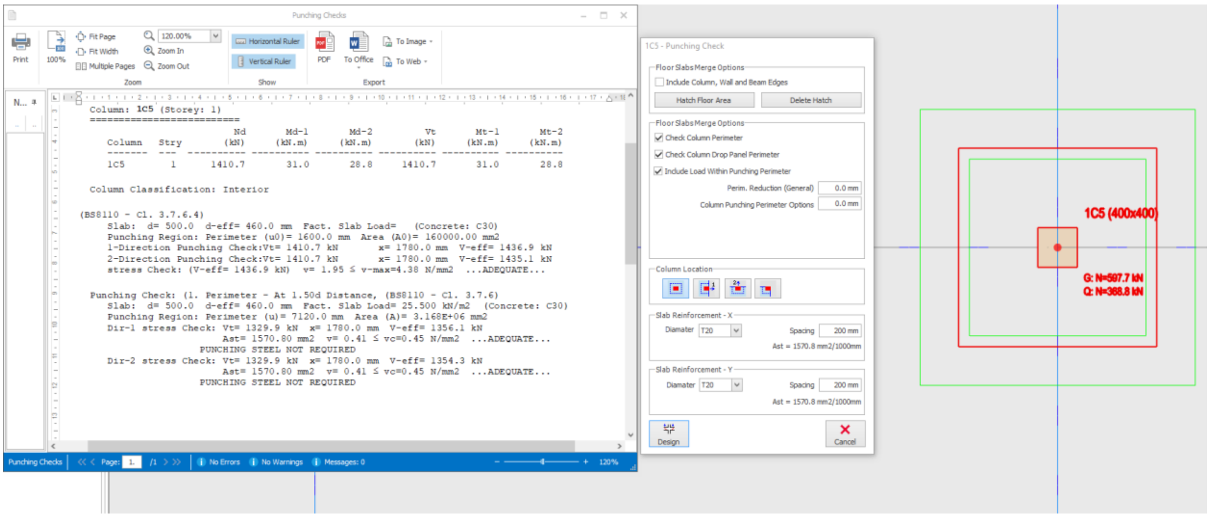


The objective of the punching check is to obtain two green perimeters as shown above. The inner perimeter (at 1.5d from the column) confirms that the drop is sufficiently deep and the outer (at 1.5d from the drop) confirms that it is sufficiently wide.

Check Punching around the Column Perimeter

For the inner perimeter shown above to be determined (and an output report created for it), the option Check Column Perimeter must be ticked on punching check dialog.

When the calculation is performed punching checks are carried out at the face of the loaded area and at the first perimeter, (both checks taking account of the increased slab depth). A red perimeter indicates that the depth of the drop panel should be increased.

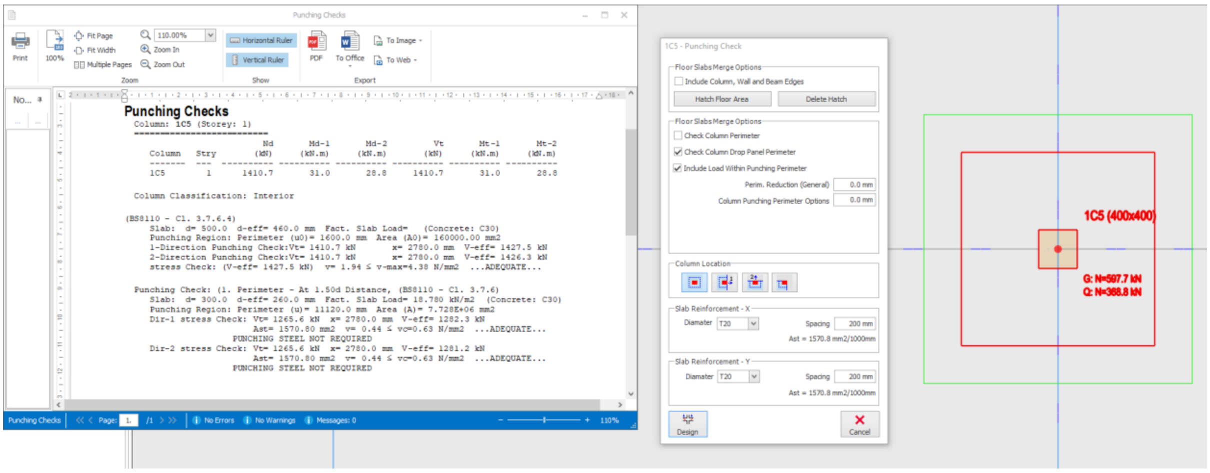


Depending on the size of panel, it is possible for the first perimeter at 1.5d to occur outside the drop panel. The calculations are then performed at this perimeter based on the increased slab depth. however, in such a case the calculation becomes irrelevant and can be ignored.

Check Punching around the Drop Panel Perimeter

The ***Check Column Drop Panel Perimeter*** option must be ticked to check the outer perimeter beyond the drop panel.

This time when the calculation is performed, a check is carried out at the face of the drop panel (taking account of the increased slab depth) and subsequent perimeters are then checked beyond this for the unthicken slab.

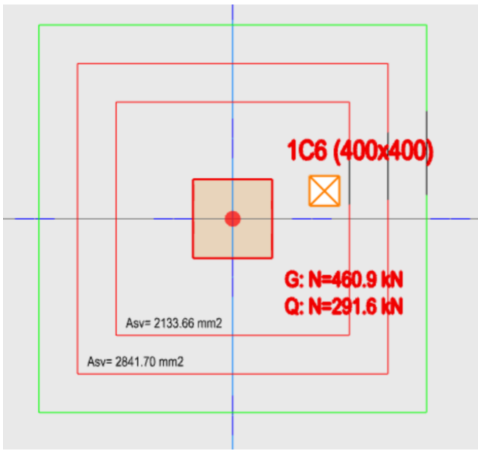


To generate a report for the results around the drop panel perimeter (as shown in the figure above), the option ***Check Column Perimeter*** should be left unticked.

If both options ***Check Column Perimeter*** and ***Check Column Drop Panel Perimeter*** are ticked, all the required checks are performed and the graphical display of the perimeters is created accordingly, however, the generated report will only display the results around the drop panel perimeter.

Dealing with Openings

Openings which have been modelled



The figure above a small hole has been positioned close to a column. On the punching perimeters that are drawn, you can then see perimeters in black (rather than red or green) indicating the lengths on the check perimeters that are excluded. The excluded length is established as the length between lines radiating from the centre of the column past each of the extreme edges of the hole.

In fact this is quite a small hole (150 mm x 150 mm square) and is actually something we would not recommend complicating the FE modelling with. We would tend to recommend that you allow for something like this by using the Perimeter Reduction Amount option. Before moving on to that, it is worth noting just how significant the reductions due to this (any) small hole can be.

Punching Checks

```
 Column: 1C6 (Storey: 1)
 ==========================
                       Nd         Md-1       Md-2         Vt       Mt-1       Mt-2
   Column   Stry      (kN)      (kN.m)     (kN.m)        (kN)     (kN.m)     (kN.m)
   -------  ---  ---------- ---------- ---------- ---------- ---------- ----------
   1C6       1      1095.6      -23.5       15.6     1095.6       23.5       15.6

 Column Classification: Interior

(BS8110 - Cl. 3.7.6.4)
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load=   (Concrete: C30)
   Punching Region: Perimeter (u0)= 1600.0 mm  Area (A0)= 160000.00 mm2
   1-Direction Punching Check:Vt= 1095.6 kN       x= 1052.3 mm  V-eff= 1129.1 kN
   2-Direction Punching Check:Vt= 1095.6 kN       x= 1180.0 mm  V-eff= 1115.5 kN
   stress Check: (V-eff= 1129.1 kN)  v= 2.71 ≤ v-max=4.38 N/mm2  ...ADEQUATE...

 Punching Check: (1. Perimeter - At 1.50d Distance, (BS8110 - Cl. 3.7.6)
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 18.780 kN/m2  (Concrete: C30)
   Punching Region: Perimeter (u)= 4460.0 mm  Area (A)= 1.392E+06 mm2
   Dir-1 stress Check: Vt= 1069.5 kN  x= 1052.3 mm  V-eff= 1103.0 kN
                       Ast= 1256.64 mm2  v= 0.95 > vc=0.59 N/mm2                  !!!
Shear Reinforcement Required !!!
                       (BS8110 - Cl. 3.7.7.5 /Eq.29b)Asv= 2133.66 mm2
   Dir-2 stress Check: Vt= 1069.5 kN  x= 1180.0 mm  V-eff= 1089.3 kN
                       Ast= 1256.64 mm2  v= 0.94 > vc=0.59 N/mm2                  !!!
Shear Reinforcement Required !!!
                       (BS8110 - Cl. 3.7.7.5 /Eq.29b)Asv= 2133.66 mm2

 Punching Check: (2. Perimeter - At 2.25d Distance, (BS8110 - Cl. 3.7.6)
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 18.780 kN/m2  (Concrete: C30)
   Punching Region: Perimeter (u)= 5940.0 mm  Area (A)= 2.465E+06 mm2
   Dir-1 stress Check: Vt= 1049.3 kN  x= 1400.1 mm  V-eff= 1074.5 kN
                       Ast= 1256.64 mm2  v= 0.70 > vc=0.59 N/mm2                  !!!
Shear Reinforcement Required !!!
                       (BS8110 - Cl. 3.7.7.5 /Eq.29a)Asv= 2841.70 mm2
   Dir-2 stress Check: Vt= 1049.3 kN  x= 1570.0 mm  V-eff= 1064.2 kN
                       Ast= 1256.64 mm2  v= 0.69 > vc=0.59 N/mm2                  !!!
Shear Reinforcement Required !!!
                       (BS8110 - Cl. 3.7.7.5 /Eq.29a)Asv= 2841.70 mm2

 Punching Check: (3. Perimeter - At 3.00d Distance, (BS8110 - Cl. 3.7.6)
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 18.780 kN/m2  (Concrete: C30)
   Punching Region: Perimeter (u)= 7420.0 mm  Area (A)= 3.842E+06 mm2
   Dir-1 stress Check: Vt= 1023.5 kN  x= 1747.9 mm  V-eff= 1043.7 kN
                       Ast= 1256.64 mm2  v= 0.54 ≤ vc=0.59 N/mm2  ...ADEQUATE...
                   PUNCHING STEEL NOT REQUIRED
   Dir-2 stress Check: Vt= 1023.5 kN  x= 1960.0 mm  V-eff= 1035.4 kN
                       Ast= 1256.64 mm2  v= 0.54 ≤ vc=0.59 N/mm2  ...ADEQUATE...
                   PUNCHING STEEL NOT REQUIRED
```

Examining the calculations above, note that:

1. **At the face of the column –** the perimeter length for the maximum shear capacity check is never reduced, although this is rarely critical by the time other checks are passing, you may want to consider the possible effect of some reduction here.
2. **At 1.5d from face –** The perimeter length is reduced by 260 mm (from 4720 mm to 4460 mm).
3. **At 2.25d from face –** The perimeter length is reduced by 340 mm (from 6280 mm to 5940 mm).
4. **At 3.00d from face –** The perimeter length is reduced by 420 mm (from 7840 mm to 7420 mm).

As expected, the reduction length is increasing. The main point to note is that a small hole of 150 mm side quite close to the face of the column reduces the punching perimeter by much longer lengths.

Providing Shear Reinforcement – The reported A_{sv} requirements relate to the effective perimeter length even though there is an unbroken full perimeter. The detailing guidance in BS8110 does not indicate whether the required reinforcement should be provided on a similarly shortened perimeter. An option to allow for this would be to factor up the A_{sv} requirement by the ratio of the full perimeter to the reduced perimeter and then provide reinforcement on the full perimeter.

Due to the almost infinite variations of intersecting slab shapes and hole shapes and positioning, it is quite possible that ProtaStructure will have difficulties accurately predicting punching perimeter reductions, this point is illustrated in the concluding notes.

Calculation of the Effective Shear Force

During punching shear checks the identified transfer force (Vt) is adjusted to allow for variations induced by transfer moments (Mt). Referring to **BS8110 clauses 3.7.6.3** and **3.7.6.4**, the applicable cases and equations are:

Internal Columns:

- For Bending in Both Directions:

$$V_{eff} = V_t \left(1 + \frac{1.5M_t}{V_t x}\right) \qquad (eq\ 25)$$

Edge Columns:

- Where bending is about an axis parallel to the free edge:

$$V_{eff} = 1.25\ V_t$$

- Where bending is about an axis perpendicular to the free edge:

$$V_{eff} = V_t \left(1.25 + \frac{1.5M_t}{V_t x}\right) \qquad (eq\ 26)$$

Corner Columns:

- For bending in both directions:

$$V_{eff} = 1.25\ V_t$$

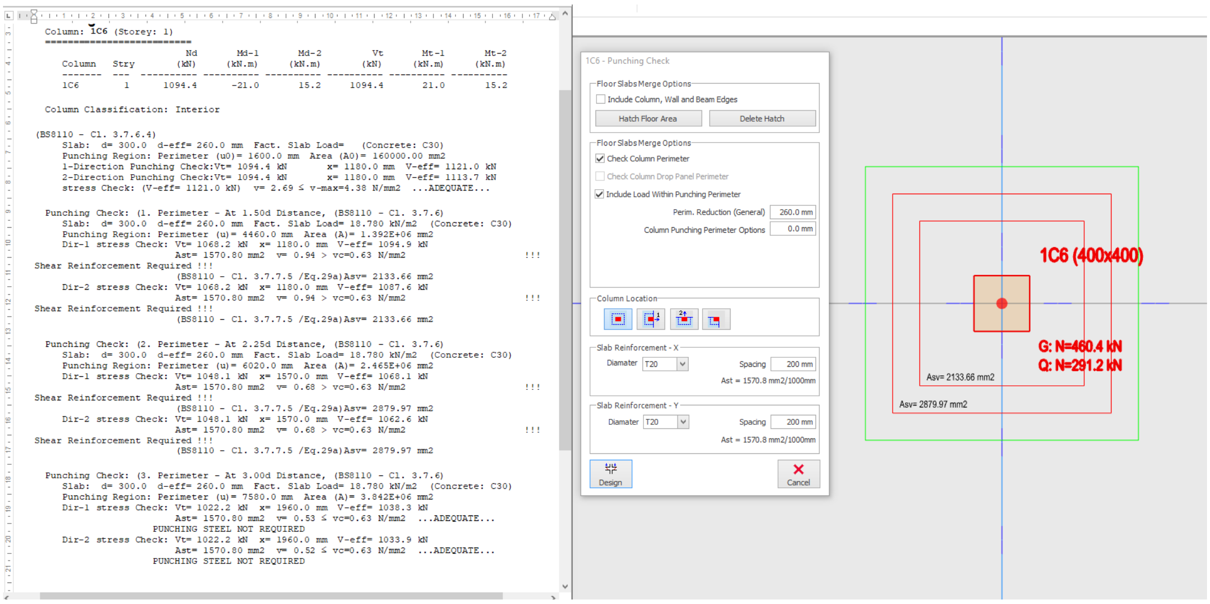
BS8110 defines **x** as the length of the side of the perimeter considered parallel to the axis of bending. There is no guidance as to whether this dimension should be shortened if openings affect the perimeter. There is no guidance on what to do when the length is shortened on one face but not on the other. Where opinions have been sought on this there is a view that **x** should not be shortened to account for openings, however no authoritative guidance has been found to this effect.

Looking to the above example, for direction 1 bending on the first perimeter one side is shortened by 260 mm. The most conservative view would be that **x** should be taken as 1180 - 393 = 820 mm. In ProtaStructure, **x** is taken as the average of the two relevant sides, in this case (1180+ 920) / 2 = 1050 mm. This is believed to be a reasonably conservative interpretation of the code requirements.

Allowing for Openings which have not been modelled

As noted above the modelling of small holes creates unnecessary complication and is often best avoided. In many projects there may also be a need to allow for holes without actually knowing for sure where they are. This can be achieved using the option to specify a perimeter reduction.

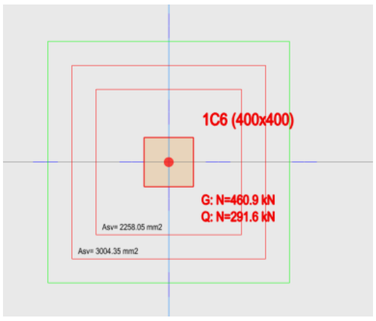
Using the same example as above and initially applying a reduction length of 260 mm (the same as ProtaStructure calculated for the first perimeter) the result is as shown below.



```
Column: 1C6 (Storey: 1)
========================
                          Nd       Md-1       Md-2         Vt       Mt-1       Mt-2
  Column   Stry         (kN)     (kN.m)     (kN.m)       (kN)     (kN.m)     (kN.m)
  -------  ---   ---------- ---------- ---------- ---------- ---------- ----------
  1C6        1       1094.4      -21.0       15.2     1094.4       21.0       15.2

Column Classification: Interior

(BS8110 - Cl. 3.7.6.4)
    Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load=   (Concrete: C30)
    Punching Region: Perimeter (u0)= 1600.0 mm  Area (A0)= 160000.00 mm2
    1-Direction Punching Check:Vt= 1094.4 kN       x= 1180.0 mm  V-eff= 1121.0 kN
    2-Direction Punching Check:Vt= 1094.4 kN       x= 1180.0 mm  V-eff= 1113.7 kN
    stress Check: (V-eff= 1121.0 kN)  v= 2.69 ≤ v-max=4.38 N/mm2  ...ADEQUATE...

  Punching Check: (1. Perimeter - At 1.50d Distance, (BS8110 - Cl. 3.7.6)
    Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 18.780 kN/m2  (Concrete: C30)
    Punching Region: Perimeter (u)= 4460.0 mm  Area (A)= 1.392E+06 mm2
    Dir-1 stress Check: Vt= 1068.2 kN  x= 1180.0 mm  V-eff= 1094.9 kN
                        Ast= 1570.80 mm2  v= 0.94 > vc=0.63 N/mm2                  !!!
Shear Reinforcement Required !!!
                        (BS8110 - Cl. 3.7.7.5 /Eq.29a)Asv= 2133.66 mm2
    Dir-2 stress Check: Vt= 1068.2 kN  x= 1180.0 mm  V-eff= 1087.6 kN
                        Ast= 1570.80 mm2  v= 0.94 > vc=0.63 N/mm2                  !!!
Shear Reinforcement Required !!!
                        (BS8110 - Cl. 3.7.7.5 /Eq.29a)Asv= 2133.66 mm2

  Punching Check: (2. Perimeter - At 2.25d Distance, (BS8110 - Cl. 3.7.6)
    Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 18.780 kN/m2  (Concrete: C30)
    Punching Region: Perimeter (u)= 6020.0 mm  Area (A)= 2.465E+06 mm2
    Dir-1 stress Check: Vt= 1048.1 kN  x= 1570.0 mm  V-eff= 1068.1 kN
                        Ast= 1570.80 mm2  v= 0.68 > vc=0.63 N/mm2                  !!!
Shear Reinforcement Required !!!
                        (BS8110 - Cl. 3.7.7.5 /Eq.29a)Asv= 2879.97 mm2
    Dir-2 stress Check: Vt= 1048.1 kN  x= 1570.0 mm  V-eff= 1062.6 kN
                        Ast= 1570.80 mm2  v= 0.68 > vc=0.63 N/mm2                  !!!
Shear Reinforcement Required !!!
                        (BS8110 - Cl. 3.7.7.5 /Eq.29a)Asv= 2879.97 mm2

  Punching Check: (3. Perimeter - At 3.00d Distance, (BS8110 - Cl. 3.7.6)
    Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 18.780 kN/m2  (Concrete: C30)
    Punching Region: Perimeter (u)= 7580.0 mm  Area (A)= 3.842E+06 mm2
    Dir-1 stress Check: Vt= 1022.2 kN  x= 1960.0 mm  V-eff= 1038.3 kN
                        Ast= 1570.80 mm2  v= 0.53 ≤ vc=0.63 N/mm2  ...ADEQUATE...
                    PUNCHING STEEL NOT REQUIRED
    Dir-2 stress Check: Vt= 1022.2 kN  x= 1960.0 mm  V-eff= 1033.9 kN
                        Ast= 1570.80 mm2  v= 0.52 ≤ vc=0.63 N/mm2  ...ADEQUATE...
                    PUNCHING STEEL NOT REQUIRED
```


Points to note are:

1. Looking at the detail of the calculations you may note that **x** is not reduced to account for the existence of un-modelled holes. This avoids what some may regard as the over conservative adjustments to **x** which ProtaStructure applies when the holes are modelled.
2. Despite the above, for the first perimeter the calculated A_{sv} requirement is identical. This is because the design in direction 2 is dominating and in direction 2, **x** was not reduced when the hole was modelled.
3. For the second perimeter, the A_{sv} requirement is a little higher because using this option the length reduction is constant on all perimeters (hence it is 260 mm rather than 340 mm). In this perimeter, min A_{sv} requirements are being used and so the requirement increases as the perimeter length increases. Given that we are only allowing for the possibility of a hole, we should check the requirements when no hole is allowed for as shown below.



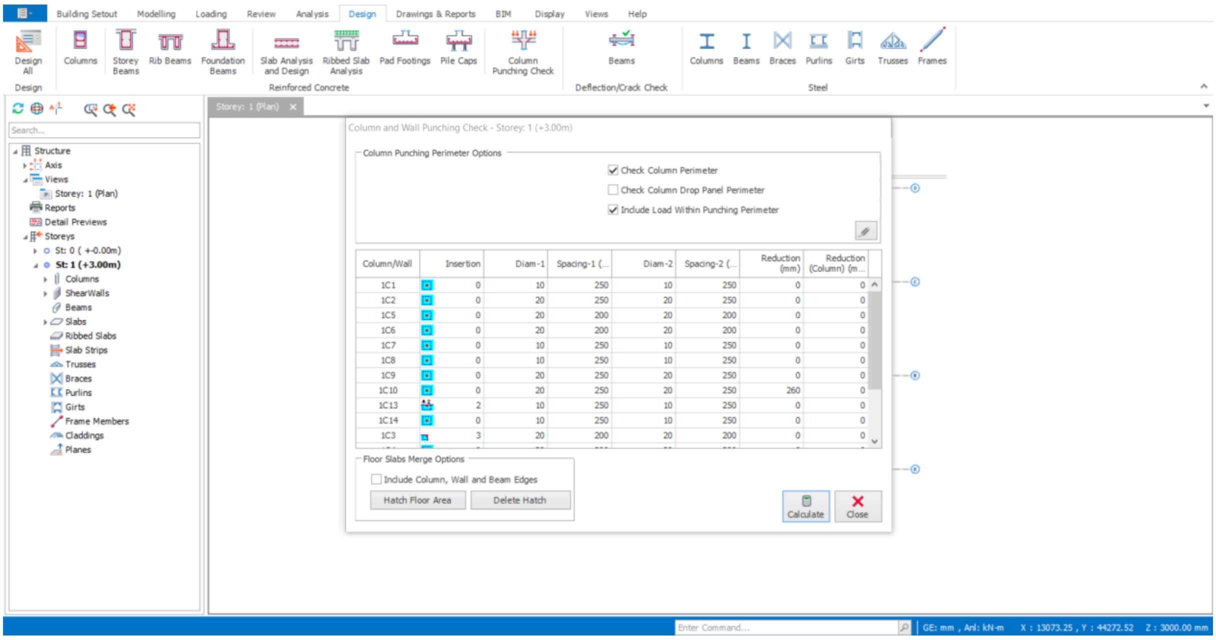
In essence, the above is exemplifying the note made earlier regarding the practicalities of providing the shear reinforcement. If the A_{sv} requirements obtained by excluding a perimeter length are factored up by the ratio of the full perimeter to the reduced perimeter so that reinforcement can then be provided on the full perimeter a very reasonable result will be achieved, perhaps erring on the side of conservatism.

In conclusion, for this model if an allowance had to be made for the possibility of holes (up to say 150 mm) adjacent to any column, it would be quite reasonable to specify a perimeter reduction of around

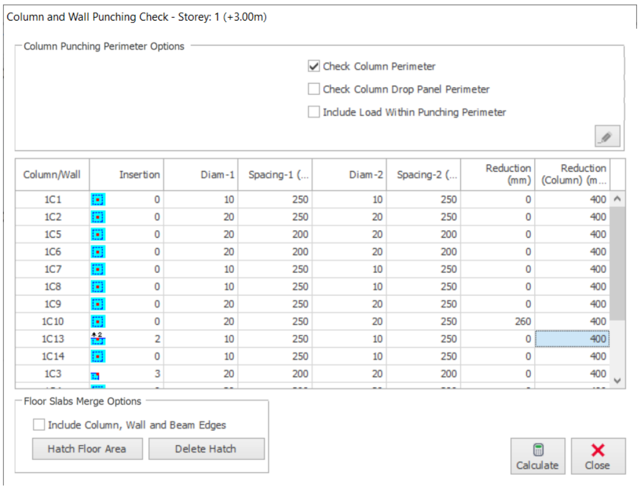
400 mm to all columns rather than take the time to attempt to model every possible hole in detail. The reported Asv requirement might then be factored up slightly to allow for the point made above.

Final Batch Check and Output

Having set up the punching design information at each column location, it is possible to rerun a batch check on punching shear for all columns as shown below.



When accessed this option will show a table where the key design information can be reviewed and adjusted if necessary.



Column/Wall	Insertion	Diam-1	Spacing-1 (...	Diam-2	Spacing-2 (...	Reduction (mm)	Reduction (Column) (m...
1C1	0	10	250	10	250	0	400
1C2	0	20	250	20	250	0	400
1C5	0	20	200	20	200	0	400
1C6	0	20	200	20	200	0	400
1C7	0	10	250	10	250	0	400
1C8	0	10	250	10	250	0	400
1C9	0	20	250	20	250	0	400
1C10	0	20	250	20	250	260	400
1C13	2	10	250	10	250	0	400
1C14	0	10	250	10	250	0	400
1C3	3	20	200	20	200	0	400

So for the final run on this model a perimeter reduction of 400 mm is applied to all columns.

<u>General Limitations</u>

Three points emphasised throughout this document are:

1. The punching shear checks required by design codes are quite empirical by nature and engineering judgement is often required as to which part of the checks are most applicable.

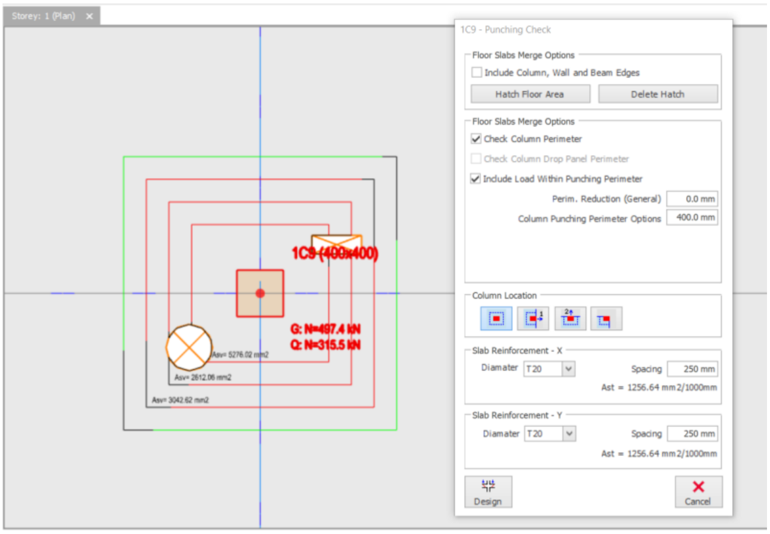
2. Potentially there are an almost infinite number of variations of intersecting slab shapes, hole shapes, discontinuous edges, etc. It is quite possible that ProtaStructure will have difficulties accurately predicting punching perimeters in many circumstances.
3. As a result, the checks must initially be carried out on one column at a time so that the engineer can take proper control over the input and review the results.

The areas in which we would particularly highlight the limitations of the current checking are:

Holes

It is possible that ProtaStructure will have difficulty identifying correct punching perimeters as the geometry of slabs and openings become more complex. The example below shows the sort of issue that could occur.

Two holes are positioned near to a column. ProtaStructure has identified the circular hole outside the check perimeters and has reduced the perimeters accordingly, the black sections of the perimeter lines can be seen on close examination.



Dimension 'x' used at the face of the loaded area

At the face of the loaded area, you will find that value of **"x"** used is the same as at the first check perimeter. It is not taken as just the column dimension. The justification for this assumption is discussed below:

- We found that when you do the check using the actual column dimensions, the column most likely to be failed. When we talked to people in the industry about this, we found that in practice they tended to ignore this check completely (assuming it to be ok by inspection) or if they did it, they just used the actual shear force and did not bother to amplify it at all, or sometimes that they just assumed the 1.15 amplification noted in Clause 3.7.6.2 would cover it. Everyone felt that the check seemed incorrect (over conservative) when applied more rigorously using the column dimensions as **"x"** at the face of a column.
- Basically, as you approach the column **"x"** decreases rapidly and so the amplification calculated in V_{eff} becomes extreme. Internal columns with ordinary transfer moments are treated as worse

cases than edge columns with very high transfer moments where the amplification of V_{eff} is a fixed value of $1.25V_t$.

- It also seems to work back to front in terms of the way it amplifies V - for example using a 600 x 300 column, if the same transfer moment is applied in both directions, the amplification of V_{eff} will be greater when bending is in the strong direction (because x=300) than when bending in the weak direction.
- Furthermore, there is the complication that **"x"** is unquantifiable for irregular and even circular column perimeters.

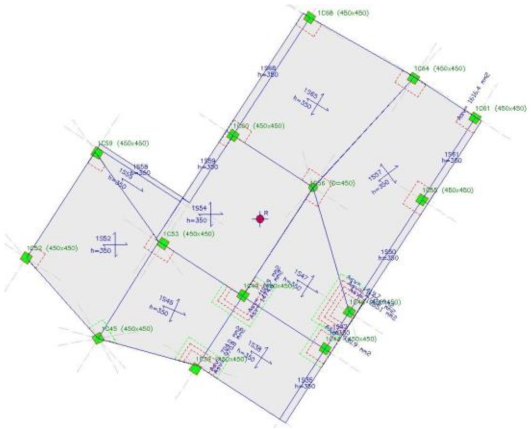
After investigations with external consultations, the conclusion arrived at was that making the same amplification as at the first check perimeter seemed reasonable and probably more conservative than what had previously been done/assumed in practice for many years.

<u>Slab Merging</u>

For ProtaStructure to be able to resolve the punching perimeter around any column all the slabs inserted around that area need to be merged into one. For simple geometries this is not a challenge. For more complex cases, it is a significant challenge where improvements have been made on an ongoing basis.

Where difficulties are encountered the floor slab merge options may help to either resolve the issue completely or isolate the problem so that the modelling can be adjusted.

The examples below are exaggerated in some respects but they do show how the features work.



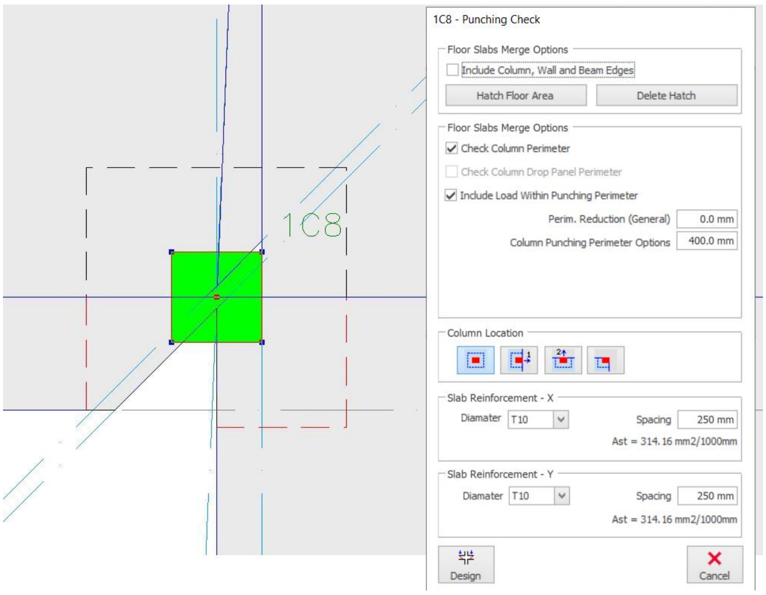
Notice that some of the punching perimeters in the slab area shown in the figure above are clearly incorrect. The option to ***Hatch Floor Area*** can be used as shown in the figure below and this shades all the slab areas that ProtaStructure has managed to merge.

Clearly, one of the slabs has not been included, the reasons why this might happen vary, but usually become apparent if the boundary of the slab is examined in close up. In this example the slab and some of the adjacent small strips do not meet properly, the slabs can be redefined and the merged floor area and punching perimeters are all then resolved as shown below.

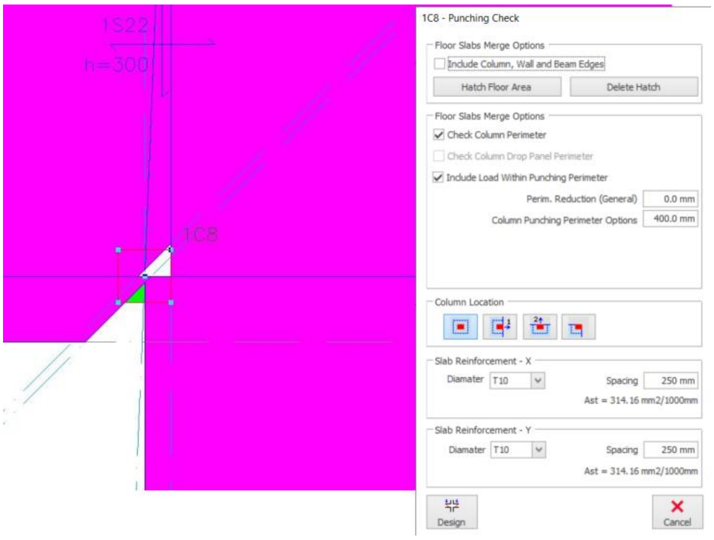
In general, it is good practice to avoid thin strips of slab and have fewer slabs wherever possible. Not only does it avoid the sort of problem shown in the figures above, but it is also less likely to cause meshing difficulties during the FE analysis.

Due to the almost infinite variations of intersecting slab shapes and hole shapes and positioning, it is quite possible that ProtaStructure will have difficulties in accurately predicting punching perimeter reductions, this point is illustrated in the concluding notes.

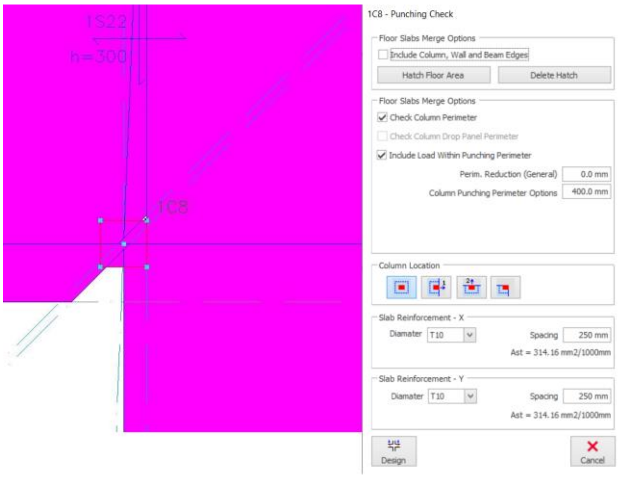
A second typical problem occurs where lots of grids meet at or near a single point. The figure below shows a column where 6 grids are meeting in close proximity and the punching shear check is showing a long section of black (missed) perimeter.

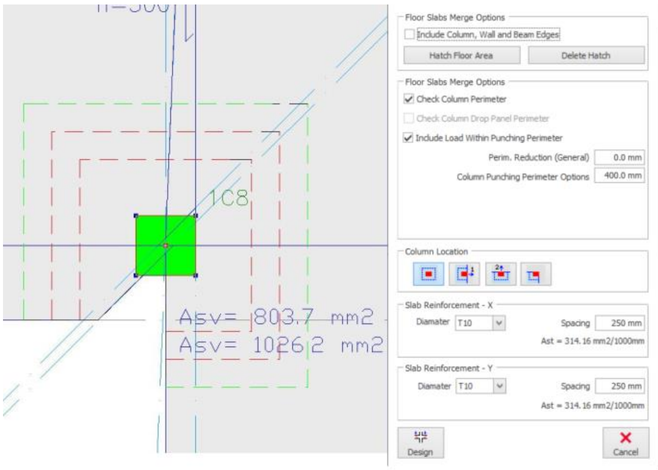


When the hatching option is used you can begin to see more clearly how the slabs have not been defined so that a triangle has been missed within the column. (This sort of problem usually occurs in smaller triangles than shown here.)



If we now check the option to ***Include the Column Wall and Beam Edges*** and then re-hatch, the area inside the column is considered as another slab area and so the merged boundary works round the perimeter of the column. This will potentially avoid all problems relating to local inaccuracies where grids meet.





The perimeters seem much more reasonable when the punching shear check is made with this option checked. Note that in this example, the missed triangle actually extends outside the column and so is considered as a hole with the resultant shortening of the punching perimeter.

Specification of Effective Slab Reinforcement

When defining the effective slab reinforcement, you can only provide one value which will apply at all the check perimeters. In practice, it is possible that lesser values of effective tension reinforcement may be applicable at perimeters further from the column perimeter. In such cases results from multiple checks may need to be used, or the more conservative (lower) value could be used for a single check across all perimeters.

Providing the Shear Reinforcement

ProtaStructure provides the design checks and information to allow the detailing to commence. As noted within the examples, the detailing is not necessarily a trivial matter, especially when allowances for holes need to be made.

Punching Perimeters

The displayed punching perimeters should look correct and complete. No examples of incorrect perimeters are shown in this document (other than the debatable perimeters shown above).

The presence of holes and/or complex irregular slab geometry may cause problems in the perimeter identification.

- For the case where holes appear to be the source of the problem, it is again worth considering removing the holes and using the option to specify a perimeter reduction.
- For the case where slab geometry appears to be the source of the problem, it is possible that the slabs can be redefined locally to avoid the problem.

Overlapping Perimeters

For the case where supports are closely spaced and perimeters overlapped, the code requires that a single combined perimeter be checked. ProtaStructure does not identify such conditions and will simply draw overlapping perimeters on the screen. If this condition occurs, additional hand calculations are required to substantiate the design.

Discontinuous Columns

In the special case where a slab supports a column or wall, Protostructure will not make any checks at all. The case remains beyond the current scope and additional hand calculations are required to substantiate the design.

Eurocode 2 Design Code Requirements

The Design Procedure

In EC2 clause 6.4 outlines the requirements for checking punching shear. ProtaStructure's punching shear check cannot be used without a reasonable understanding of the code's requirements. The following notes provide a brief overview of these.

Cl. 6.4.3 describes the basic design procedure; shear capacity is checked at the face of the column and then at the basic control perimeter. If shear reinforcement is required a further perimeter is established at which shear reinforcement is no longer required.

Check Maximum Shear Capacity at Face of The Column

This is a check at the face of the loaded area, refer to clause 6.4.5(3) of EC2.

The length of the shear perimeter at the column face may be calculated in accordance with clause 6.4.5(3).

Note this only provides specific design guidance for rectangular columns with this guidance being further limited, for the case of edge and corner columns, to those cases where the edge(s) of the slab coincide with the edge(s)of the column.

Therefore, for other column shapes and scenarios ProtaStructure must modify the equations presented in EC2. It is considered that the equations used by ProtaStructure will result in either the correct perimeter length being obtained or a conservative value (i.e. an underestimate of the perimeter length).

Check Shear Capacity at the Basic Control Perimeter

The basic control perimeter is at 2d from the face of the column (the loaded area), where d is the average effective depth of the tension reinforcement.

To make an accurate check on this perimeter the following needs to be known/controlled:

- Is it an internal/edge/corner condition?
- How much main reinforcement is effective?
- Are there holes, for which you need to account?

The shear stress at the modified basic control perimeter, $v_{Ed,1}$ is calculated from Eqn. 6.38 as follows:

$$v_{Ed,1} = V_t/(u_1 d)$$

The punching shear resistance of slab without punching shear reinforcement, $v_{Rd,c}$ is then calculated at the basic control perimeter. Three results are possible:

1. If $v_{Ed,1} > v_{Rd,max}$ the slab thickness is inadequate, the check has failed and no further calculations is possible for the particular column. The slab needs to be re-designed.

else if $v_{Ed,1} < v_{Rd,max,}$ then check whether $v_{Ed,1} \geq v_{Rd,c}$:

2. If $v_{Ed,1} \leq v_{Rd,c,}$ the punching shear resistance of the slab is adequate without the provision of shear reinforcement. No further calculations are necessary.

else if $v_{Ed,1} \geq v_{Rd,c}$, then shear reinforcement is required and check whether $v_{Ed,1} \geq 2v_{Rd,c}$ to comply with UK National Annex to BS EN 1992-1-1:2004 Eq.6.4.5 (3):

3. If $v_{Ed,1} \geq 2v_{Rd,c}$, the slab depth is insufficient and hence the slab needs to be re-designed.

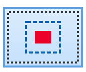
Calculate Shear Reinforcement Required and Length of Outer Control Perimeter

The quantity of shear reinforcement required when the shear stress at the basic control perimeter, $v_{Ed,1}$, exceeds the shear strength of the slab without shear reinforcement, $v_{Rd,c}$ is calculated using clause 6.4.5(1) and Eqn. 6.52.

The length of perimeter where shear reinforcement is not required, u_{out} is calculated from Eqn 6.54.

Calculation of Magnification Factor

As with BS8110, EC2 increases the basic punching shear force to obtain the design punching shear force, when an unbalanced bending moment is transferred between the slab and column. In EC2 this design punching shear force is obtained by multiplying the basic punching shear force by the magnification factor which has a value greater than 1.0. The purpose of this section is to detail the way in which ProtaStructure determines the value for various column situations.

<u>Internal column</u> 

It is calculated using the equation:

$$Magnification\ factor = 1 + k1\left(\frac{M_{t1}}{V_t}\right)\left(\frac{u_1}{W_{11}}\right) + k2\left(\frac{M_{t2}}{V_t}\right)\left(\frac{u_1}{W_{12}}\right)$$

Where;

- k_1 and k_2 are factors from Table 6.1 depending on the column aspect ratio for the direction M_{t1} and M_{t2} are the transferred moments in the two orthogonal directions.
- V_t is the transferred shear force.
- u_1 is the length of the basic control perimeter located at 2.0d from the face of the column.
- W_{11} and W_{12} are the first moments of the basic control perimeter about the two axes (see the section on calculation of W_1 below).

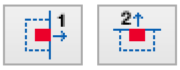
The length of the basic control perimeter is modified to take account of the presence of actual physical holes in accordance with 6.4.2(3) and the first moment of area of the perimeter is calculated based on this reduced length.

For the case where the presence of holes is represented by a value of the Perimeter Reduction (General) greater than zero then, since the actual location of the loss of perimeter is unknown, the value of is calculated as follows:

$$Magnification\ factor = 1 + \left(\frac{u_1}{u_{1,red}}\right)\left[k1\left(\frac{M_{t1}}{V_t}\right)\left(\frac{u_1}{W_{11}}\right) + k2\left(\frac{M_{t2}}{V_t}\right)\left(\frac{u_1}{W_{12}}\right)\right]$$

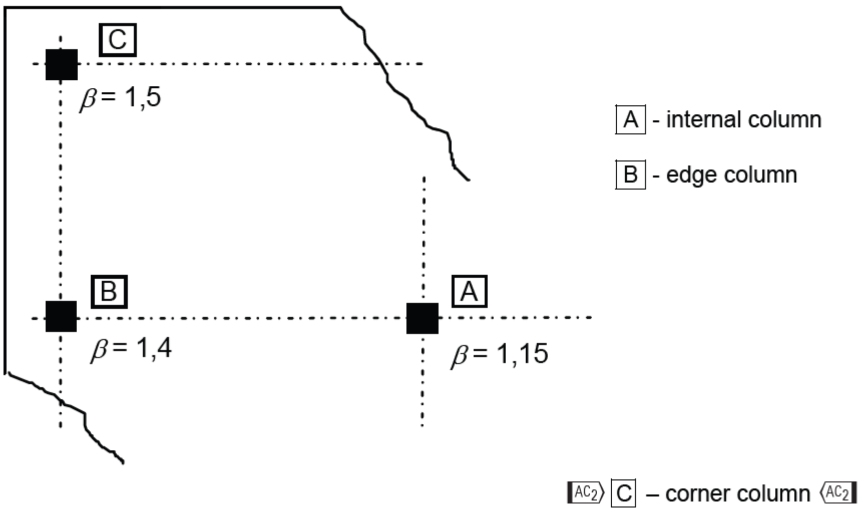
Where;

- Where u_1 is the full perimeter length i.e., not reduced by Perimeter Reduction
- $u_{1,\,red}$ is the reduced perimeter length i.e., reduced by Perimeter Reduction
- W_{11} & W_{12} are both calculated based on the full perimeter length

<u>Edge column</u> 

If the user chooses not to select the column to be treated as an edge column, the value of will be calculated as for an internal column as detailed above, taking account of the presence of the edge of the slab.

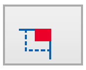
If the user selects the column to be treated as an edge column, then β is taken as 1.4 as in Figure 6.21 of EC2.



The value of β is calculated using the equation 6.44 which is effectively the generic equation 6.39. The effects of the moments about the two orthogonal axes are then combined using simple addition as follows:

$$Magnification\,factor = 1.4 + k\left(\frac{M_t}{V_t}\right)\left(\frac{u_1}{W_{11}}\right)$$

where k, M_t and W_1 all relate to bending about the axis perpendicular to the edge of the slab. Where actual physical holes are present or the Perimeter Reduction is greater than zero, W1 is calculated as described for an internal column but taking account of the location of the edge of the slab.

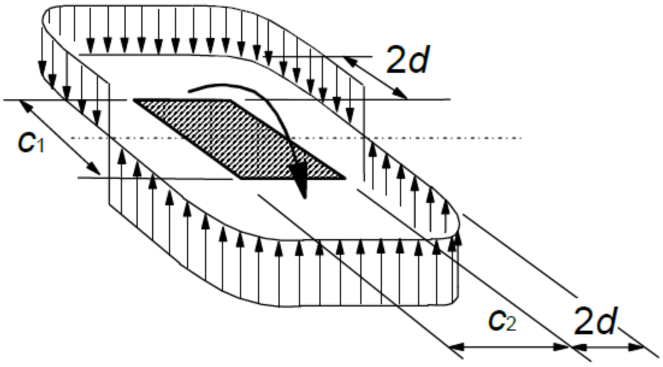
<u>Corner column</u> 

If users choose not to select the column be treated as a corner column the value of will be calculated as for an internal column as detailed above, taking account of the presence of the edge of the slab.

If the user selects the column be treated as a corner column, the value of will be taken as 1.5 from Figure 6.21 of EC2 with no additional calculation. The value of 1.5 is not adjusted if actual physical holes are present or if the Perimeter Reduction is greater than zero.

Calculation of W_1

EC 2 describes W_1 as a factor which *"corresponds to a distribution of shear as illustrated in Figure 6.19 and is a function of the basic control perimeter u1"*.



W_1 may be calculated from equation 6.40 as follows:

$$W_i = \int_0^{u_i} |e|dl$$

Note the equation is integral between limits 0 & u which u is over the full length of the perimeter where l is a length increment of the perimeter and |e| is the modulus of the distance of the increment from the axis about which the moment acts or in other words W_1 = the first moment of the perimeter about the axis about which the moment acts.

Alternatively, W_1 for rectangular column can be calculated by equation 6.41.

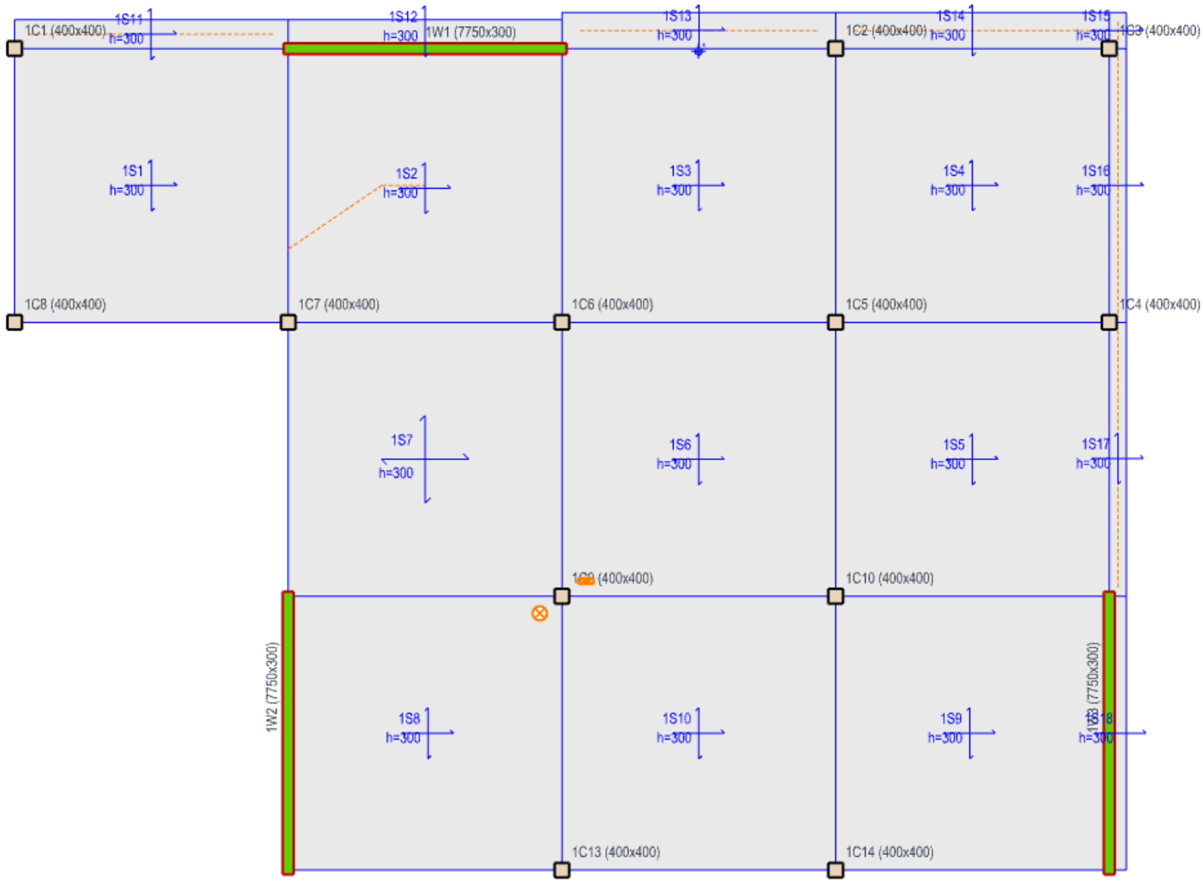
$$W_1 = \frac{c_1^2}{2} + c_1c_2 + 4c_2d + 16d^2 + 2\pi dc_1 \qquad \text{(Eq. 6.41)}$$

For edge column, W_1 will be taken as per equation 6.45

$$W_1 = \frac{c_1^2}{4} + c_1c_2 + 4c_1d + 8d^2 + \pi dc_2 \qquad \text{(Eq. 6.45)}$$

Simple EC 2 Examples

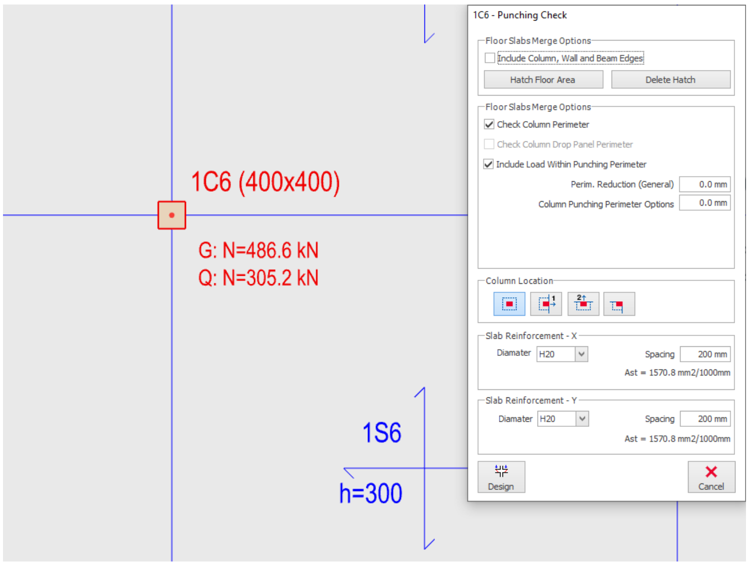
In this section we will look at a series of relatively simple EuroCode examples using the model shown below.



- A typical internal column.
- The effects of openings.

The model is set out on a regular **7.5 m** grid, the slab is **300 mm** thick with **0.5 kN/m²** finishes and **5.0 kN/m²** imposed load. The columns are **400 mm** square.

Checking a Typical Internal Column



Performing the Check

In the view above column 1C6 is selected, right click and select the Column Punching Check option to expose the punching check tab as shown.

<u>Floor Slab Merging Options</u>

- Check Column Perimeter and Check Column Drop Panel Perimeter (only active if a drop has been defined) – These options allow the check on maximum shear capacity at the face of the loaded area to be toggled on and off.
- Perimeter Reduction (General) – An allowance for holes that have not been modelled or may be cut in the future.
- Include Load Within Punching Perimeter – When this option is checked the shear load considered on each successive punching perimeters will reduce (due to the increasing area of loading that falls within the punching perimeter. When un-checked the shear load will be the same on all perimeters – i.e., the check becomes more conservative.
- Column Punching Perimeter Options – These options would be used in cases where the punching perimeters are not found (generally in cases of complex slab geometry).

<u>Column Location</u>

- As will be illustrated in the following examples, it is the user's responsibility to indicate the location (internal/edge/corner).

<u>Slab Reinforcement X (and Y)</u>

- The effective area of tension reinforcement in each direction must be input manually.

Checking Maximum Shear Stress at the Face of the Column

According to Eq. 6.38, the maximum shear stress at face of column should be taken as:

$$V_{Ed,max} = \frac{\beta V_{Ed}}{u_i d_{eff}}$$

For internal rectangular column where the loading is eccentric to both axes, β will be calculated with equation below:

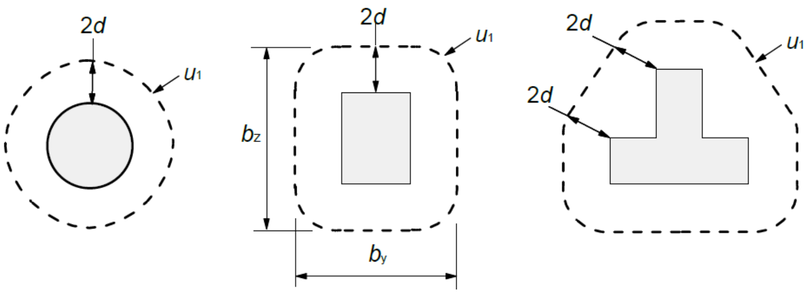
$$Magnification\ factor = 1 + k1\left(\frac{M_{t1}}{V_t}\right)\left(\frac{u_1}{W_{11}}\right) + k2\left(\frac{M_{t2}}{V_t}\right)\left(\frac{u_1}{W_{12}}\right)$$

Where;

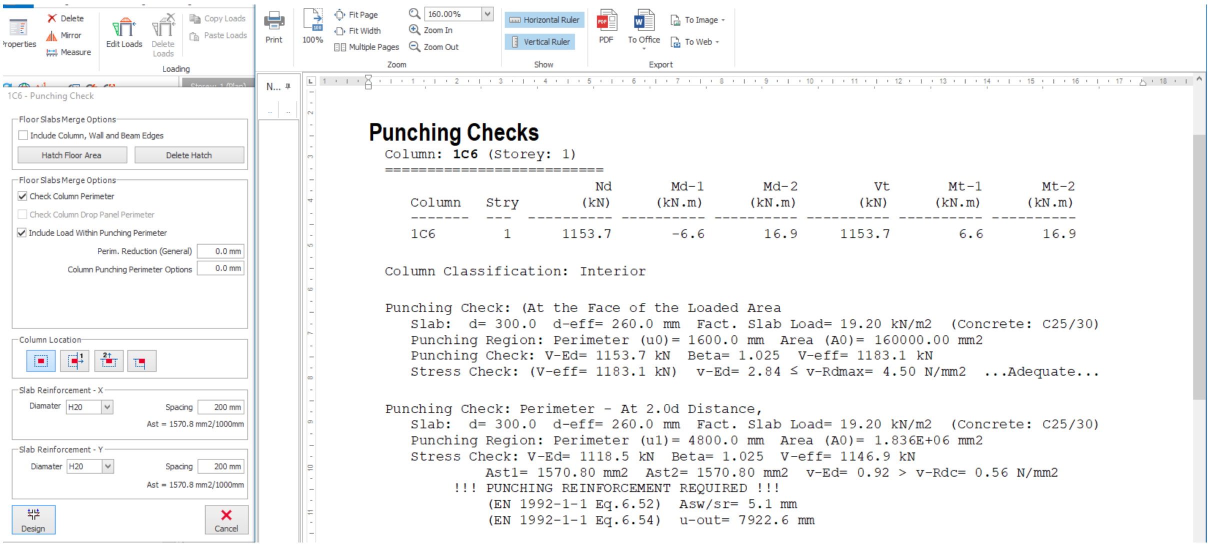
- k_1 and k_2 are factors from Table 6.1 depending on the column aspect ratio for the direction M_{t1} and M_{t2} are the transferred moments in the two orthogonal directions.
- V_t is the transferred shear force.
- u_1 is the length of the basic control perimeter located at 2.0d from the face of the column.
- W_{11} and W_{12} are the first moments of the basic control perimeter about the two axes.

Where,

- e_y and e_z are the eccentricities M_{Ed}/V_{Ed} along y and z axes respectively.
- b_y and b_z is the dimensions of the control perimeter (see Figure 6.13).



If no changes are made and the column is checked with the settings as shown in the figure below, the result will be generated and shown in another window.



Punching Checks

```
Column: 1C6 (Storey: 1)
==========================
                          Nd        Md-1        Md-2          Vt        Mt-1        Mt-2
   Column   Stry        (kN)      (kN.m)      (kN.m)        (kN)      (kN.m)      (kN.m)
   -------  ---   ----------  ----------  ----------  ----------  ----------  ----------
   1C6        1       1153.7        -6.6        16.9      1153.7         6.6        16.9

Column Classification: Interior

Punching Check: (At the Face of the Loaded Area
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 19.20 kN/m2  (Concrete: C25/30)
   Punching Region: Perimeter (u0)= 1600.0 mm  Area (A0)= 160000.00 mm2
   Punching Check: V-Ed= 1153.7 kN  Beta= 1.025  V-eff= 1183.1 kN
   Stress Check: (V-eff= 1183.1 kN)  v-Ed= 2.84 ≤ v-Rdmax= 4.50 N/mm2  ...Adequate...

Punching Check: Perimeter - At 2.0d Distance,
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 19.20 kN/m2  (Concrete: C25/30)
   Punching Region: Perimeter (u1)= 4800.0 mm  Area (A0)= 1.836E+06 mm2
   Stress Check: V-Ed= 1118.5 kN  Beta= 1.025  V-eff= 1146.9 kN
            Ast1= 1570.80 mm2  Ast2= 1570.80 mm2  v-Ed= 0.92 > v-Rdc= 0.56 N/mm2
        !!! PUNCHING REINFORCEMENT REQUIRED !!!
            (EN 1992-1-1 Eq.6.52)  Asw/sr= 5.1 mm
            (EN 1992-1-1 Eq.6.54)  u-out= 7922.6 mm
```

<u>Calculation of effective depth, d-eff</u>

- Thickness of the slab, d = 300 mm
- Concrete cover for slab = 20
- Slab reinforcement diameter in X-direction = 20mm (H20)
- Slab reinforcement diameter in Y-direction = 20mm (H20)

$d - eff\ in\ X - direction,$

$$d - eff_x = h - concrete\ cover - \frac{bar\ x}{2} = 300 - 20 - \frac{20}{2} = \mathbf{270\ mm}$$

$d - eff\ in\ Y - direction,$

$$d - eff_y = h - concrete\ cover - barx - \frac{bar\ y}{2} = 300 - 20 - 20 - \frac{20}{2} = \mathbf{250\ mm}$$

$$d - eff\ = \frac{d - eff_x + d - eff_y}{2} = \mathbf{260\ mm}$$

Calculation of magnification factor, β

$$Magnification\ factor, \beta = 1 + k1\left(\frac{M_{t1}}{V_t}\right)\left(\frac{u_1}{W_{11}}\right) + k2\left(\frac{M_{t2}}{V_t}\right)\left(\frac{u_1}{W_{12}}\right)$$

- k_1 and k_2 = 0.6 (taken from Table 6.1)
- M_{t1} = 6.6 kN.m
- M_{t2} = 16.9 kN.m
- V_{Ed} = 1153.7 kN
- u_1 = 4800 mm
- W_{11} and W_{12} = 2391051.27 mm calculated as per Eq. 6.41.

$$Magnification\ factor, \beta = 1 + 0.6\left(\frac{6.6 * 1000}{1153.7}\right)\left(\frac{4800}{2391051.27}\right) + 0.6\left(\frac{16.9 * 1000}{1153.7}\right)\left(\frac{4800}{2391051.27}\right) = \mathbf{1.025}$$

Calculation of maximum shear stress at face of the column, $V_{Ed,max}$

- V_{Ed} = 1153.7 kN
- U_0 = 1600 mm
- β = 1.025
- d_{eff} = 260 mm

$$V_{Ed,max} = \frac{\beta V_{Ed}}{u_0 d_{eff}} = \frac{(1.025 \times 1153.7 \times 1000)}{(1600 \times 260)} = \mathbf{2.84}\ {}^{\boldsymbol{N}}/_{\boldsymbol{mm^2}}$$

Calculation of maximum punching resistance adjacent to column, $V_{Rd,max}$

According to Cl. 6.4.5 (3), the value of VRd,max for use in a Country may be found in its national Annex. In this example, $V_{Rd,max}$ is calculated by using equation below:

$$v_{Rd,max} = 0.5 v f_{cd}$$

Where,

$$v = 0.6\left(1 - \frac{f_{ck}}{250}\right) \qquad \text{(Eq. 6.6N)}$$

$$v_{Rd,max} = 0.5 \times 0.6\left(1 - \frac{f_{ck}}{250}\right) \times \alpha_{cc} \times {}^{f_{ck}}/_{1.5} = 0.5 \times 0.6\left(1 - \frac{25}{250}\right) \times 1.0 \times {}^{25}/_{1.5} = \mathbf{4.5\ N/mm^2}$$

Maximum shear stress at column face, $v_{Ed,max}$, 2.84 N/mm^2 is lower than the maximum punching resistance adjacent to column, $v_{Rd,max}$, 4.5 N/mm^2. Hence, the slab design is adequate.

The slab depth is insufficient if $v_{Ed,max}$ is higher than the $v_{Rd,max}$. The slab needs to be re-designed.

Capacity at the Basic Control Perimeter (2d from the face of the column)

Punching Checks

```
Column: 1C6 (Storey: 1)
==========================
                          Nd        Md-1        Md-2          Vt        Mt-1        Mt-2
   Column   Stry         (kN)      (kN.m)      (kN.m)        (kN)      (kN.m)      (kN.m)
   -------  ---  ----------- ----------- ----------- ----------- ----------- -----------
   1C6        1       1153.7        -6.6        16.9      1153.7         6.6        16.9

Column Classification: Interior

Punching Check: (At the Face of the Loaded Area
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 19.20 kN/m2  (Concrete: C25/30)
   Punching Region: Perimeter (u0)= 1600.0 mm  Area (A0)= 160000.00 mm2
   Punching Check: V-Ed= 1153.7 kN  Beta= 1.025  V-eff= 1183.1 kN
   Stress Check: (V-eff= 1183.1 kN)  v-Ed= 2.84 ≤ v-Rdmax= 4.50 N/mm2  ...Adequate...

Punching Check: Perimeter - At 2.0d Distance,
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 19.20 kN/m2  (Concrete: C25/30)
   Punching Region: Perimeter (u1)= 4800.0 mm  Area (A0)= 1.836E+06 mm2
   Stress Check: V-Ed= 1118.5 kN  Beta= 1.025  V-eff= 1146.9 kN
            Ast1= 1570.80 mm2  Ast2= 1570.80 mm2  v-Ed= 0.92 > v-Rdc= 0.56 N/mm2
        !!! PUNCHING REINFORCEMENT REQUIRED !!!
            (EN 1992-1-1 Eq.6.52)  Asw/sr= 5.1 mm
            (EN 1992-1-1 Eq.6.54)  u-out= 7922.6 mm
```

Calculation of shear stress at basic control perimeter, $v_{Ed,1,max}$

- u_1 = 4800 mm
- V_{Ed} = 1118.5 kN

$$V_{Ed,1,max} = \frac{\beta V_{Ed}}{u_1 d_{eff}} = \frac{(1.025 \times 1118.5 \times 1000)}{(4800 \times 260)} = \mathbf{0.92}\ {}^{\boldsymbol{N}}/_{\boldsymbol{mm^2}}$$

Calculation of concrete punching shear capacity (without shear reinforcement), $V_{Rd,c}$

According to clause 6.4.4 (2), $v_{Rd,c}$ is calculated by following equation below:

$$v_{Rd,c} = C_{Rd,c} k (100\, \rho_1 f_{ck})^{1/3} \geq v_{min}$$

where

- a is the distance from the perimeter of the column to the control perimeter considered.
- $C_{Rd,c}$ is $0.18/\gamma_c$ as defined in 6.4.4(1).
- k is $1 + \sqrt{\frac{200}{d}} \leq 2.0$ as defined in 6.4.4(1).
- v_{min} is $0.035 k^{3/2} {f_{ck}}^{1/2}$ as defined in 6.4.4(1).

Punching shear reinforcement is required when the value of $v_{Rd,c}$ exceeds:

$$v_{Ed,1,max} \geq v_{Rd,c} \qquad \text{(Eq.6.4.3 (2b))}$$

UK National Annex to Eurocode 2 suggests that $v_{Ed,1,max}$ should be limited to $2v_{Rd,c}$ at the first control perimeter:

$$v_{Ed,1,max} \geq 2 \times v_{Rd,c}$$

(NA to BS EN 1992-1-1: 2004 Eq.6.4.5 (3))

Slab needs to be redesigned if $v_{Ed,1,max}$ exceeds $2V_{Rd,c}$ limit as the slab depth is insufficient.

$$C_{Rd,c} = \frac{0.18}{1.5} = 0.12$$

$$k = 1 + \sqrt{\frac{200}{d}} = 1.87 \leq 2.0$$

$$v_{\min} = 0.035k^{3/2}{f_{ck}}^{1/2} = 0.448\ N/mm^2$$

$$\rho_{1x} = \frac{Ast_x}{(1000 \times d_{eff})} = \frac{1570.80}{1000 \times 260} = 0.006042$$

$$\rho_{1y} = \frac{Ast_y}{(1000 \times d_{eff})} = \frac{1570.80}{1000 \times 260} = 0.006042$$

$$\rho_1 = (\rho_{1x} \times \rho_{1y})^{1/2} = 0.006042$$

$$a = 2 \times d = 2 \times 260 = 520\ mm$$

$$v_{Rd,c} = C_{Rd,c}k(100\ \rho_1 f_{ck})^{1/3} = 0.12 \times 1.87 \times (100 \times 0.006042 \times 25)^{1/3} = \mathbf{0.56\ N/mm^2} \geq \left(v_{min} = \mathbf{0.45}\ {}^{\boldsymbol{N}}\!/\!_{\boldsymbol{mm^2}}\right)$$

Hence, $v_{Rd,c} = 0.56$ N/mm²

Check if $v_{Ed,1,max} \geq v_{Rd,c}$:

$$v_{Ed,1,max} = 0.92\ N/mm^2 \geq v_{Rd,c} = 0.56\ N/mm^2,$$
$$\boldsymbol{hence\ punching\ shear\ reinforcement\ is\ required}$$

Check if $v_{Ed,1,max} \geq 2 \times v_{Rd,c}$:

$$v_{Ed,1,max} = 0.92\ N/mm^2 \leq 2 \times v_{Rd,c} = 1.12\ N/mm^2,$$
$$\boldsymbol{hence\ the\ slab\ depth\ is\ sufficient.}$$

The value of $v_{Ed,1,max}$, 0.91 N/mm² is higher than $V_{Rd,c,}$ 0.56 N/mm² and not exceeding $2V_{Rd,c}$ limit. It indicates that the punching shear resistance of the slab is inadequate without the provision of shear reinforcement. Hence, shear reinforcement is required.

<u>Calculation of shear reinforcement of one perimeter around the column.</u>

According to EC 2, punching shear resistance of slabs and column bases with shear reinforcement, $V_{Rd,cs}$ is calculated in accordance with Eq. 6.52.

$$v_{\mathrm{Rd,cs}} = 0{,}75\ v_{\mathrm{Rd,c}} + 1.5\ (d/s_{\mathrm{r}})\ A_{\mathrm{sw}}\ f_{\mathrm{ywd,ef}}\ (1/(u_1 d))\ \sin\alpha$$

After transposing the equation above, shear reinforcement per perimeter can be calculated as:

$$\mathrm{A}_{\mathrm{sw}} = (\mathrm{v}_{\mathrm{ED,1,max}} - 0.75\ \mathrm{v}_{\mathrm{Rd.c}})\ \mathrm{u}_1 \mathrm{s}_r\ /\ (1.5\ \mathrm{f}_{\mathrm{ywd.ef}})$$

or

$$\mathrm{A}_{\mathrm{sw}}/_{\mathrm{s}_r} = (\mathrm{v}_{\mathrm{ED,1,max}} - 0.75\ \mathrm{v}_{\mathrm{Rd.c}})\ \mathrm{u}_1\ /\ (1.5\ \mathrm{f}_{\mathrm{ywd.ef}})$$

where

$$f_{ywd.ef} = 250 + 0.25d \ \leq f_{ywd}$$

which is also:

$$f_{ywd.ef} = 250 + 0.25d \ \leq f_{yd}/1.15$$

Concise Eurocode 2 which published in 2006 also states that vertical shear reinforcement per perimeter is assumed as the equation above.

- $v_{ED,1,max}$ = 0. 92 N/mm^2
- $v_{Rd.c}$ = 0.56 N/mm^2
- u_1 = 4800 mm
- $f_{ywd.ef}$ = 315 N/ mm^2 ≤ 434.78 N/ mm^2
- d = 260 mm

$$A_{\,sw}/_{s_r} = \frac{(0.92 - 0.75 \times 0.56)4800}{(1.5 \ \times 315)} = 5.1$$

Calculation of the control perimeter at which reinforcement is not required ($u_{out,ef}$).

$$u_{out,ef} = \frac{\beta V_{Ed}}{(V_{Rd,c} \times d)}$$

(Eq.6.54)

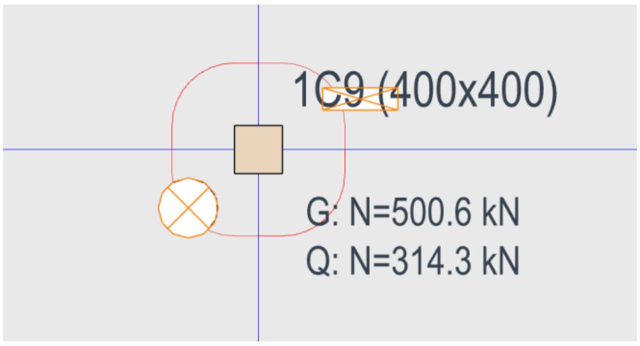
- $V_{ED,1}$ = 1118.5 kN
- $v_{Rd.c}$ = 0.56 N/mm^2
- β = 1.025
- d = 260 mm

$$u_{out,ef} = \frac{(1.025 \ \times \ 1118.5 \ \times 1000)}{(0.56 \times 260)} = 7874.06\, mm$$

```
Punching Check: Perimeter - At 2.0d Distance,
   Slab:  d= 300.0  d-eff= 260.0 mm  Fact. Slab Load= 19.20 kN/m2  (Concrete: C25/30)
   Punching Region: Perimeter (u1)= 4800.0 mm  Area (A0)= 1.836E+06 mm2
   Stress Check: V-Ed= 1118.5 kN  Beta= 1.025  V-eff= 1146.9 kN
            Ast1= 1570.80 mm2  Ast2= 1570.80 mm2  v-Ed= 0.92 > v-Rdc= 0.56 N/mm2
        !!! PUNCHING REINFORCEMENT REQUIRED !!!
            (EN 1992-1-1 Eq.6.52)  Asw/sr= 5.1 mm
            (EN 1992-1-1 Eq.6.54)  u-out= 7922.6 mm
```

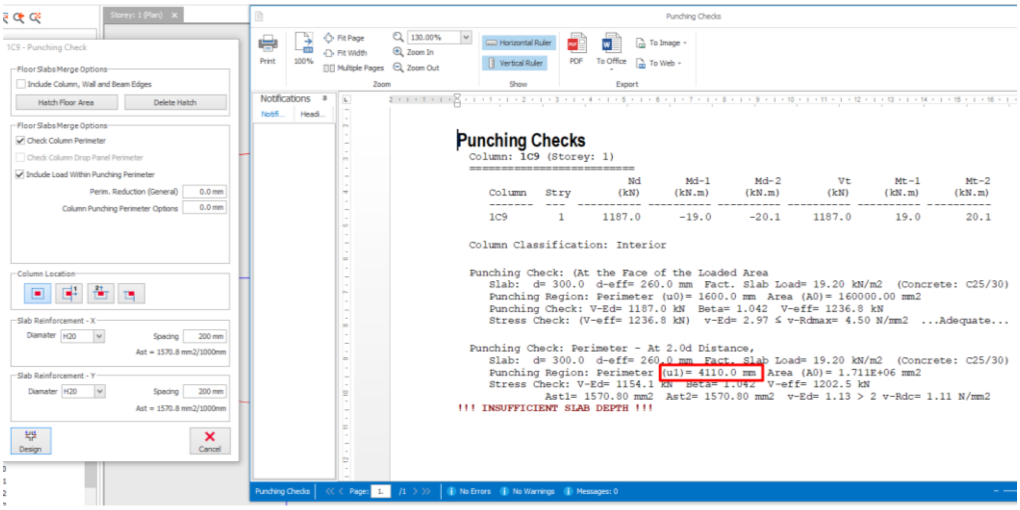
Dealing with Openings

Openings which have been modelled



The figure above shows 2 small openings has been positioned close to column 1C9. On the punching perimeters that are drawn, you can see that there is reduction on the basic control perimeter.

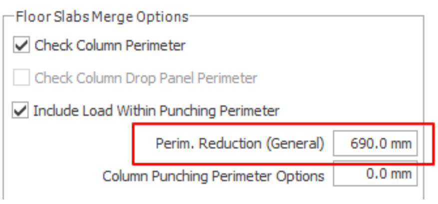
In previous internal column example, the length of basic control perimeter at 2d from column face (u_1) is 4800 mm. For Column 1C9, the value of u_1 is certainly shorter due to adjacent openings. This can be verified by checking value of u_1 in column punching checks report.



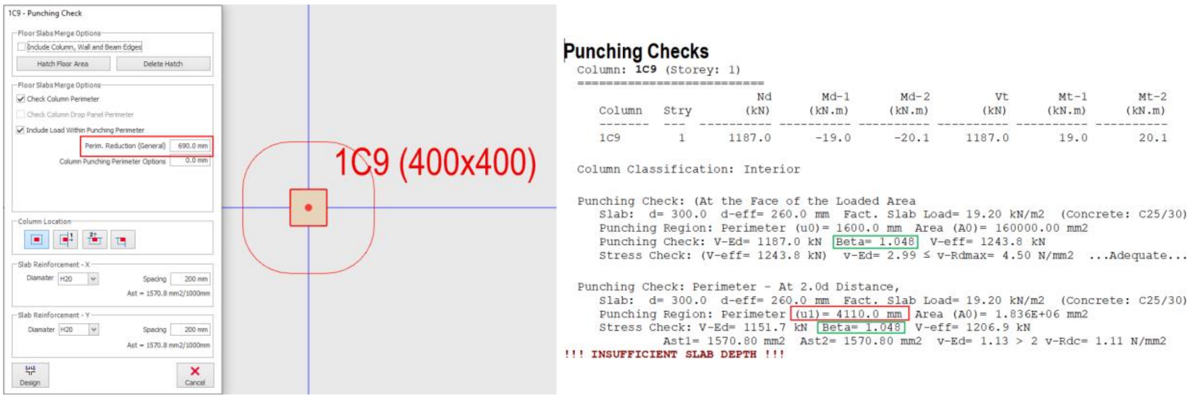
As shown in the report, u_1 of 1C9 with 2 openings is 4110 mm which is 690 mm shorter than the column with no openings.

Allowing for Openings which have not been modelled

As noted above the modelling of small holes creates unnecessary complication and is often best avoided. In many projects there may also be a need to allow for holes without knowing for sure where they are. This can be achieved using the option to specify a perimeter reduction in Perimeter Reduction (General).



Using the same example as above, and initially applying a reduction length of 690 mm (the same as ProtaStructure calculated for the first perimeter) the result is as shown below.



Hence, perimeter reduction (General) option allows users to consider openings which could be included in future.

Furthermore, for the case where the presence of holes is represented by a value of the Perimeter Reduction (General), the value of β is calculated as follows:

$$\beta = 1 + \left(\frac{u_1}{u_{1,red}}\right)\left[k1\left(\frac{M_{t1}}{V_t}\right)\left(\frac{u_1}{W_{11}}\right) + k2\left(\frac{M_{t2}}{V_t}\right)\left(\frac{u_1}{W_{12}}\right)\right]$$

$$\beta = 1 + \left(\frac{4800}{4110}\right)\left[0.6\left(\frac{19.0 \times 1000}{1187}\right)\left(\frac{4800}{2391051.27}\right) + 0.6\left(\frac{20.1 \times 1000}{1187}\right)\left(\frac{4800}{2391051.27}\right)\right] = \mathbf{1.048}$$

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