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SIMPLIFIED MODELING OF V-SHAPED BRIDGE PIERS

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Designing a steel, V-shaped bridge pillar requires a complex and detailed finite element calculation model. The calculation can be simplified by using a simple one-dimensional beam model, but then the stress concentrations are not determined in detail. The use of a stress concentration factor, SCF, to make this possible. Before using this method, it is first verified whether both models behave correspondingly, by calculating the internal forces certain sections. Five basic load cases are used to perform this verification. Afterwards the stress concentration factors are determined for those same load cases. This method induces inconsistencies, some predictable but others unpredictable. The conclusion can however be that this simplified meth gives unreliable results. Therefore, a second method is used, where the high stresses in the curvatures of the pillar are related to the stresses in a nearby neutral section. Such a neutral section is defined as a section where the stress peaks due to the geometric effects caused by the actual geometry of the nodes of the V-shaped pilar are not present anymore. This method provides better results for the SCF; however, some issues remain, which are discuss in more detail in the paper. Finally, the impact of a varying radius of curvature on the stresses is also studied. Some clear trends are observed in this paper Overall, this paper discusses a possible simplified design method for V-shaped bridge pillars, at the same time listing the relevant design difficulties and possible pitfalls of a too simplified model.

Keywords: Stress concentration factors, Fatigue, Simplifications, Bridge supports, Steel.

1 INTRODUCTION

V-shaped piers are becoming rather popular for long viaducts, from the 90's on, up to date. However, most of these piers are concrete, the steel alternative being rare. The need for rapid construction increases the popularity among designers to consider steel V-shaped pillars. The latter show considerable horizontal resistance to braking and acceleration loads. In buildings they are sometimes valued for their smooth shape. The pillars for the new bridge across the Ourthe in Tilff are a steel example, however this one is placed orthogonal to the expected direction. Steel V-shaped pillars are more complex to design than the concrete equivalent. A detailed plate model is required to take the local effects of the curvatures at the corners into account (BAM Galere 2018).

2 FINITE ELEMENT MODELLING - PLATE MODEL

The design of the plate model is based on plans of an existing V-column in a building and the method of Janssens (2020). The dimensions of this column are then scaled up to obtain realistic dimensions of a bridge pillar. The dimension in the frontal plane is shown in Figure 1, where no curvatures are added yet. Curvatures are added in all the corners, creating a smoother shape. This shape is then transformed into the 3D model of the pillar. The 2D view is tilted slightly forward,



as the depth of the base is 1500 mm while at the top it is 1000 mm. Afterwards the top beam is added, which has a height of 714 mm.



Figure 1. The dimensions of the plate model in the front plane (left) and the detailed plate model (right).

In this paragraph the Von Mises stresses are analyzed, to observe the overall behavior of the pillar (The European Union 2003). Figure 2 (left) plots the Von-Mises stresses σ_{E+} under the general load case. The subscript + indicates the outer fiber on which the stresses occur. The stresses are observed at the critical locations, so around the curvatures. The same method of obtaining the stresses is also used for the rest of this paper, which will focus on these critical locations. High stresses occur at the upper plate of the top beam, related to the application of the loads. This local effect is not studied as it is not the objective of this paper, but also because these are easily solved by locally increasing the plate thickness. The peaks in the curvatures are more interesting and will be the focus. Figure 2 (right) gives a closer look at one of these critical locations. A peak stresses occurs at the connection of the curved plate with the front and the back plate. The peak stresses itself cannot be used, as these are unrealistic. An average stress is used over a distance equal to the plate thickness. Multiple lines are drawn starting in the stress peak, so at the plate edges, and are oriented away from it.



Figure 2. Von-Mises stresses under a general load case (left) and in one of the curvatures (right).



3 FINITE ELEMENT MODELLING - BEAM MODEL

The beam model consists out of four elements: a horizontal beam on top, two oblique elements on the side and a vertical element on the bottom. These are modelled in SCIA Engineer as lines with a cross-section corresponding to the plate model. These lines run through the center of the corresponding parts of the plate model, shown as the green lines in Figure 3. The oblique elements must be lengthened to connect to the top beam and to each other at the bottom. As a result, the vertical element at the bottom is required to be shorter. Determining the cross-sections of the top beam and the vertical element is straight forward, as these both have a rectangular cross-section. The oblique elements require some attention. The cross-section varies along the length, but these must continue further on than the plate model. The linear shape of the plates must be extended to find the cross-section at both ends. This is shown in red on Figure 3. External forces and moments on the pillar are shown in Figure 4.



Figure 3. Geometry of the beam model.



Figure 4. External forces and moments on the pillar.

3 STRESS CONCENTRATION FACTORS

Now that both models are modelled as corresponding, a comparison between them can be searched. This is done by means of stress concentration factors. These factors provide a number with which a stress value in the neutral section of the beam model must be multiplied to find the actual stress



in the critical zones of the plate model. In this way, the designer only must use a simplified beam model to get to know the critical stresses.

To find the stress concentration factors, the neutral sections as verified in Section III will be used. Because it was proven the plate model only corresponds to the beam model for the side on which the forces are applied, the following neutral sections shown in Figure 5 will be used. Section C is from the right beam, but this will be used to see which one of the sections B or C is best to compare with for curvature R_3 .



Figure 5. The neutral sections used in the beam model (left), the curvatures used in the plate model (middle), and the locations of the curvatures and neutral sections(right).

Curvature R4 is split up to be able to compare them to section C or D. In the end, no good results are found for this SCF. The beam model gives an average stress over the whole cross section which results in a lot of sign changes in the stresses. Local compression in the plate model and tension as the average in the beam model cannot be trusted to compare with each other. A more accurate approach should be used to find an SCF.

Curvature	Stress	Average SCF	Diff.
R1	σ_x	2.55	1.41
	σ_y	4.66	3.46
	τ_{xy}	3.99	0.25
R2	σ	1.00	0.25
	σ_y	4.17	6.27
	τ_{xy}	1.72	1.42
R4	σ	1.88	1.48
	$\sigma_{\rm y}$	8.04	1.08
	τ_{xy}	3.99	0.25

Table 1.	The SCFs	of the	plate	model
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Therefore, the SCF of the plate model is searched. This has the advantage that it can use the maximum in the neutral section and not the average. This would lead to a more representable value as neutral stress. Because the beam model will be forgotten in this section, the curvatures R1 and R2 on the other side of the structure are used. These curvatures are located further from the application of the forces which could influence the results. The curvatures and neutral sections tested are shown in Figure 5. The SCF's found using this method are much better than the ones found while comparing to the beam model. Neglecting some useless results, a constant SCF could be found except for curvature R3. The other results are added in Table 1, which gives the average value and the difference of the maximum and minimum value of the considered SCF.

At last, the radii of the curvatures are changed to see what effect this has on the SCF. For every curvature, four other magnitudes are tested, two larger and two smaller than the original radius.



Due to the different radii per curvature, it can be easily seen on a graph at which location the best neutral section occurs by looking for stresses over the whole length of the beam. The best location for a neutral section will then be the point where the stresses in function of the length of the beam stop being linear. Figure 6 shows the results for section A near curvature R1 as an illustration. The different curves are the maximum Von-Mises stresses for the different radii of curvature, over the length of the top beam due to external load F_x . The location of the neutral section is shown in red.



Figure 6. The determination of the location of a neutral section.

This is done, but it turned out the SCF is worse at these optimized neutral sections. Therefore, it is chosen to continue with the maximum of the stresses instead of the SCF's from this point on. They will give the exact same curves in function of the radius and represent the absolute values.

The results of curvature R1 are used as an example to show this. Figure 7 shows the results in curvature R1 for respectively σ_x and σ_y . Only the stresses in curvature R1 are considered, as the stresses at the other locations are not influenced by a varying radius R1.



Figure 7. Variation of the stresses σ_x (left) and σ_y (right) in R1.

The stress results generally tend to curve towards zero for an increasing radius, by following a parabolic shape. This is very clear for σ_y under the external load F_y . But the stresses σ_x under the horizontal load F_x remain constant in the considered interval. Also, the stress σ_y under the external moment M_z increases slightly when the radius of curvature is increased.

In most cases this results in a parabolic curve where the stresses decrease in function of a larger radius. In some cases, it is the other way around and the stresses increased for an increasing radius. Due to the small number of tests, it is not clear yet if this is an error or if this phenomenon is real.



At first sight, no errors occurred in these results, and it happened more than once. Overall, the tested radii are too large, and the range might be too small to see a clear curve. When looking to much smaller radii, a better approach can be used to make conclusions as of now, some cases seem to stay linear which seems not realistic.

4 CONCLUSIONS

To use an SCF factor relating the plate model to the beam model, both are required to correspond to each other. This is only the case under some conditions, as shown in Section III. The determination of the SCF's also led to reliability issues related to the obtained stresses. Thus, the use of this method does not seem as a safe and reliable method.

If the SCF are related to the stresses in the plate model itself, the results improve. This method seems as a more stable and trustworthy method.

Thirdly some conclusions can be made about the effect of a varying curvature on the stresses. Changing the curvature in one location does not influence the results at other curvatures. For most cases, the stresses decrease with an increasing radius. However, this could not always be proven for some specific scenarios where the stresses increase with an increasing curvature.

This master thesis shed some light on the possibilities, but also the difficulties of the design of V-shaped pillars. Although there are some issues, the results are still very promising. With possible future research the design of such type of pillars can be facilitated significantly, which drastically reduces the required amount of work.

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