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Transverse Resonant Vibration of Non-Bearing Structures Caused by Wind

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Abstract. Nowadays, there are increasing use of very thin, subtle and light structures in the field of building constructions. We can find such a structures as part of roofs or design facades. By using these lamellas like, non-bearing structures as a part of architectural design of buildings, it is necessary to consider wind effects on these structures. Subtle structures of this type are prone to vibration in the transverse direction of the wind flow. The fact that the vibration occurs depends on wind parameters (wind velocity, direction of an air flow) and it also depends on the properties of lamella (shape, length, mass, natural frequency, support type). The principal idea of this article is to show susceptibility of lamellae-like structures to transverse resonant vibration caused by the phenomenon called Von Karman effect. Comparison of susceptibility to transverse resonance vibration was analysed on the different shapes of lamellas loaded by different wind speed. Analysis was based on usage of empirically derived equations. Von Karman effect arise from wind flow past an object. Turbulence in the form of vortices are formed at the object and shed into the flowing stream intermittently. The potential problem is that this turbulence can induce vibrations into the lamella itself. In terms of this vibration problem, two frequencies are interesting. Von Karman shedding frequency is the frequency at which the vortices are formed and shed at the object. The vortex-shedding frequency increases with the velocity of the wind flow and decreases with the size of the object. Natural frequency of the object depends on the construction of the lamella itself. Parameters of lamella as a shape, mass, length, elasticity modulus of material and support types are directly involved in the calculation of natural frequency. Worst case scenario in the term of transverse resonant vibration occurs when the natural frequency of lamella is equal to the vortex-shedding frequency. In this case vibration rises and structure can be snapped or deformed permanently. In the long term vibration, fatigue stress can be significant. At the conclusion hazardous wind speed and recommendations for different shapes and parameters of lamellas are shown.

1. Introduction
The fundamental objective of this paper is to point out on transverse resonant vibration problem of non-bearing, lamellae-like structures, caused by Von Karman air vortices. Structures of this type can be found mostly as a part of roofs or facades. Due to very thin, subtle and light design, they are at the risk of oscillation caused by many factors. One of the most frequently occurring problem is the oscillation of the structure in transverse direction caused by production of vortices on both sides of the object.

Von Karman vortex street arise from wind flow past an object, where vortices at high angular velocities compared to the wind flow velocity are produced on both sides of the object. On one side
clockwise rotating vortices and on the other side counter-clockwise rotating vortices separate periodically. As a result of the alternating low-pressure vortices on the downstream side of the object it tends to move toward the low-pressure zone. If the frequency of vortex shedding matches the resonance frequency of the structure, the structure begins to resonate and vibrates in harmonic oscillations driven by the energy of the flow. In this case vibration rises and structure can be damaged or deformed permanently. For the long term vibration, fatigue stress can be significant. To avoid these problems, proper design of structure has to be created and more detail analysis of shape and design should be performed. Comparison of 3 cross-sections (rectangle, triangle and circle) of lamellae-like structure was done. Different wind speed and boundary conditions of the analyzed lamellas were compared. As a result, suitability of usage of different shapes of lamellas in terms of prevention of Von Karman transverse resonant vibration is shown.

![Figure 1. Examples of the lamellas - lamellas on the facade [1] and lamellas on the roof](image)

2. Analysis of non-bearing structures
The analysis is based on the identifying of the boundary frequencies, where structure tends to oscillate. Problem of transverse vibration caused by Von Karman air vortices arises, when the natural frequency of lamella is equal to the vortex-shedding frequency.

Methodology of the analysis is as follows. Three cross sections of variable lengths and sizes were selected. Chart of dependency between natural frequency of lamella and its length was created. In this case, first natural frequency of the structure was calculated. Subsequently, vortex-shedding frequency was calculated and marked to the chart. At the higher natural frequencies, it is assumed, that the vibrations caused by Von Karman effect should not be significant and therefore, higher natural frequencies are neglected. Intersection of the curve showing natural frequency with the lines showing boundary vortex-shedding frequencies represents interval of the lamella lengths, where transverse resonant vibrations could occur. Structures were analyzed as both sides clamped and also as a both sides simple supported (hinged).

2.1. Properties of analyzed structure
Three, in engineering practice frequently used cross-sections were chosen. Cross-sections are shown in the figure 2. Equilateral hollow triangle, hollow circle and hollow rectangle were selected for the analysis. Material was selected as a structural steel with properties listed in the table 1. Selected dimensions and properties of cross-sections are also listed in the table 1.

![Figure 2. Selected cross-sections - a) equilateral hollow triangle, b) hollow rectangle, c) hollow circle](image)
Table 1. Dimensions and properties of selected cross-sections

|               | a [mm] | b [mm] | t [mm] | I [m^4]       | m [kg/m] | E [GPa] |
|---------------|--------|--------|--------|--------------|----------|---------|
| Triangle 1    | 50     | -      | 2      | 5.0668e-8    | 2.177    | 210     |
| Triangle 2    | 120    | -      | 4      | 1.4511e-6    | 10.584   | 210     |
| Rectangle 1   | 120    | 60     | 4      | 8.4766e-7    | 10.733   | 210     |
| Rectangle 2   | 160    | 50     | 4      | 7.2822e-7    | 12.605   | 210     |
| Circle 1      | 70     | -      | 3      | 4.5326e-7    | 6.469    | 210     |
| Circle 2      | 120    | -      | 5      | 2.9919e-6    | 14.090   | 210     |

* Symbols used in the table 1 are shown and explained in the figure 2 and in the subsection 2.2.

2.2. Natural frequency of the analyzed structures

The natural frequency of the structure is dependent only on the stiffness of the structure and the mass which participates with the structure (in this case self-weight). It is not dependent on the load function.

For the calculation of the first natural frequency of the given examples (both sides clamped and both sides simple supported), equations (1) respectively (2) where used, [2].

Equation (1) is used for the calculation of the natural frequency of the simple supported beam:

$$ f = \frac{9.87}{2\pi L^2} \sqrt{\frac{EI}{m}} $$

Equation (2) is used for the calculation of the natural frequency of the both sides fixed (clamped) beam:

$$ f = \frac{22.4}{2\pi L^2} \sqrt{\frac{EI}{m}} $$

where: $E$ is Young’s modulus [N/m²], $I$ is Moment of inertia of the cross section [m^4], $m$ is Mass/Unit length [kg/m], $L$ is Length of lamella [m].

Charts showing natural frequency of each lamella are listed below in the results section.

2.3. Transverse resonant vibration – Von Karman effect

An obstacle in the wind flow will produce vortices on both sides at high angular velocities compared to the flow velocity. On the one side of the object clockwise rotating vortices are created, on the other side counter clockwise rotating vortices are created. As a result of repeating pattern of swirling vortices on the downstream side of the object, it tends to move toward the low-pressure zone. A vortex street will only form at a certain range of flow velocities, specified by a range of Reynolds numbers ($Re$), which can be seen in the figure 3.

Reynolds number ($Re$) is a dimensionless quantity used to help predict flow patterns in different flows. Reynolds number is defined by equation (3), [3].

$$ Re = \frac{vd}{v} $$

Where: $v$ is the wind speed with the respect to the object [m/s], $d$ is the characteristic dimension of the object [m],
\( \nu \) is the kinematic viscosity of the fluid [m\(^2\)/s]. In the figure 3 visualization of the flow past a circular cylinder for different Reynolds numbers is shown.

In the sub-critical zone, \( \text{Re} \) is \( 2 \times 10^5 - 3 \times 10^5 \). Vortexes are separated alternately on both sides of the object. Two stable, rotating vortices are created with the frequency of vortex separation defined by equation (4), [5, 6].

\[
\text{Re} = 2.5 \times 10^5
\]

\[
\text{Re} = 3.8 \times 10^5
\]

\[
\text{Re} = 5.3 \times 10^5
\]

\[
\text{Re} = 6.5 \times 10^5
\]

**Figure 3.** Flow past a circular cylinder from critical to super-critical Reynolds numbers, [4]

In the critical and super-critical zone, \( \text{Re} \) is \( 3 \times 10^5 - 5 \times 10^6 \). Vortexes are separated irregularly and vortex-shedding frequency is no longer the predominant frequency. Separation of the vortexes is random through the whole frequency spectrum.

\[
n = \frac{\nu St}{d}
\]  \hspace{1cm} (4)

Where: \( \nu \) is the wind speed with the respect to the object [m/s],

\( St \) is the Strouhal number [-] obtained by experimental measurements, for the purposes of the analysis it was taken from [5, 7],

\( d \) is the characteristic dimension of the object [m].
In the trans-critical zone, Re is larger than $5 \times 10^6$. Separation of vortexes is partially random, partially periodical. Frequency of the separation of vortexes can be calculated by equation (4), however the value of the Strouhal number is greater.

2.4. Vortex-shedding frequency, natural frequency of the lamella and critical wind speed.
Most of the year, periodic wind gusts do not exceed wind speed 20 m/s. The lower limit of wind speed where periodic wind gusts occurs is 5 m/s. It is assumed, that higher or lower wind speed should no longer cause the Von Karman transverse resonant vibration of the lamellas. It is due to the fact, that gust of the wind of the higher or lower wind speeds cannot act periodically, therefore periodic vortexes cannot arise. Reynolds number for all analyzed cases is between $1.7 \times 10^4 - 1.7 \times 10^5$. Therefore, it can be said, that sub-critical respectively turbulent flow with lower Re is the matter of interest here and vortices would separate at a well-defined frequency ($n$), calculated by equation (4).

When lower and upper boundaries of wind speed are known, it is possible to rewrite equation (4) and calculate critical frequencies corresponding to wind speed (5 and 20 m/s). By rewriting the equation (4) critical frequencies for analyzed structures were calculated. Results are shown in the table 2.

| Table 2. Critical vortex-shedding frequencies |
|----------------------------------------------|
| St $[-]$ | d [mm] | $n$ [Hz] (corresponding to $v = 5$ m/s) | $n$ [Hz] (corresponding to $v = 20$ m/s) |
| Triangle 1 | 0.24 | 50 | 24.0 | 96.0 |
| Triangle 2 | 0.24 | 120 | 10.0 | 40.0 |
| Rectangle 1 | 0.06 | 60 | 5.0 | 20.0 |
| Rectangle 2 | 0.09 | 50 | 9.0 | 36.0 |
| Circle 1 | 0.18 | 70 | 12.9 | 51.4 |
| Circle 2 | 0.18 | 120 | 7.5 | 30.0 |

In a subsequent step, equations (1) and (2) were used for the calculation of the natural frequencies of different cross sections with different length and methods of fixation. By calculation of these values, curve of dependency between natural frequency and its length was created. To determine the length of the lamella where transverse resonant vibration could occur, intersection between critical vortex-shedding frequency (corresponding to 5 and 20 m/s) and the curve of dependency between natural frequency and its length have to be created.

3. Results of the analysis
In the following figures, charts of dependencies between natural frequency and length of lamella are shown. Due to the fact, that in engineering practice it is almost impossible to create “perfect” hinge respectively “perfect” clamp fixation, it should be considered that actual method of fixation is somewhere between hinge and clamp. Therefore, due to safety reasons, lengths of lamellas corresponding to critical frequencies where calculated for both cases (both sides simple supported and both sides clamped). On the vertical axis frequency is shown and on the horizontal axis length of lamella is shown. Critical frequency corresponding to wind speed 5 m/s respectively 20 m/s is shown by the horizontal dot lines. Intersection of horizontal dot line with the curves of dependency between natural frequency and length creates point, which could be characterized on horizontal axis as a critical length of the lamella. Between upper and lower critical frequency, there is a set of lengths (shown on the horizontal axis), where it is a risk of transverse resonant vibration caused by Karman vortex street. Lamellas of this critical (risky) lengths should not be used or they should be alternatively equipped with aerodynamic baffles, which prevents formation of periodical vortexes.
3.1. Results of the analysis - hollow triangles

**Figure 4.** Frequency-length chart showing critical values of lamella length

**Figure 5.** Frequency-length chart showing critical values of lamella length

**Table 3.** Critical lengths corresponding to vortex-shedding frequency of triangular lamellas

| Windward size d [mm] | Critical length - simple supported \( L \) [m] (corresponding to \( v = 5 \text{ m/s} \)) | Critical length - simple supported \( L \) [m] (corresponding to \( v = 20 \text{ m/s} \)) | Critical length - clamped \( L \) [m] (corresponding to \( v = 5 \text{ m/s} \)) | Critical length - clamped \( L \) [m] (corresponding to \( v = 20 \text{ m/s} \)) |
|----------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| Triangle 1           | 50                                       | 2.1                                      | 1.1                                      | 3.2                                      | 1.6                                      |
| Triangle 2           | 120                                      | 5.2                                      | 2.6                                      | 7.8                                      | 3.9                                      |
Simple supported lamella named as a “Triangle 1” faces the risk of transverse resonant vibration when the length is in zone between 1.1 – 2.1 m. Lamella named as a “Triangle 2” faces the risk when the length is in zone between 2.6 – 5.2 m. When a clamp fixation is provided, the “Triangle 1” faces the risk of transverse resonant vibration when the length is in zone between 1.6 – 3.2 m and the “Triangle 2” faces the risk when the length is in zone between 3.9 – 7.8 m.

3.2. Results of the analysis - hollow rectangles

![Frequency-Length chart; cross section - Rectangle 1](image1)

![Frequency-Length chart; cross section - Rectangle 2](image2)

**Figure 6.** Frequency-length chart showing critical values of lamella length

**Figure 7.** Frequency-length chart showing critical values of lamella length

**Table 4.** Critical lengths corresponding to vortex-shedding frequency of rectangular lamellas

| Windward size | Critical length - simple supported - L [m] (corresponding to v = 5 m/s) | Critical length - simple supported - L [m] (corresponding to v = 20 m/s) | Critical length - clamped - L [m] (corresponding to v = 5 m/s) | Critical length - clamped - L [m] (corresponding to v = 20 m/s) |
|---------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|
| Rectangle 1   | 60                                                                           | 6.4                                                                          | 3.2                                                              | 9.6                                                              |
| Rectangle 2   | 50                                                                           | 4.4                                                                          | 2.2                                                              | 6.6                                                              |
Simple supported lamella named as a “Rectangle 1” faces the risk of transverse resonant vibration when the length is in zone between 3.2 – 6.4 m. Lamella named as a “Rectangle 2” faces the risk when the length is in zone between 2.2 – 4.4 m. When a clamp fixation is provided, the “Rectangle 1” faces the risk of transverse resonant vibration when the length is in zone between 4.8 – 9.6 m and the “Rectangle 2” faces the risk when the length is in zone between 3.3 – 6.6 m.

3.3. Results of the analysis - hollow circles

**Table 5. Critical lengths corresponding to vortex-shedding frequency of circular lamellas**

| Windward size d [mm] | Critical length - simple supported - L [m] (corresponding to \( v = 5 \text{ m/s} \)) | Critical length - simple supported - L [m] (corresponding to \( v = 20 \text{ m/s} \)) | Critical length - clamped - L [m] (corresponding to \( v = 5 \text{ m/s} \)) | Critical length - clamped - L [m] (corresponding to \( v = 20 \text{ m/s} \)) |
|----------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| Circle 1             | 70                                                       | 3.8                                                      | 1.9                                                      | 5.8                                                      | 2.9                                                      |
| Circle 2             | 120                                                      | 6.7                                                      | 3.3                                                      | 10.0                                                     | 5.0                                                      |
Simple supported lamella named as a “Circle 1” faces the risk of transverse resonant vibration when the length is in zone between 1.9 – 3.8 m. Lamella named as a “Circle 2” faces the risk when the length is in zone between 3.3 – 6.7 m. When a clamp fixation is provided, the “Circle 1” faces the risk of transverse resonant vibration when the length is in zone between 2.9 – 5.8 m and the “Circle 2” faces the risk when the length is in zone between 5.0 – 10.0 m.

4. Conclusions

It is clear from the above results, that there is no ideal lamella shape, which would be absolutely resistant to transverse resonant vibration caused be Von Karman vortex street.

However, it can be said, that cross section named as a “Circle 2” appears to be the best for shorter spans. When the length of lamella with cross section “Circle 2” does not exceed 3.3 m, it should be safe in terms of Von Karman transverse resonant vibration. On the other hand, longer lamellas of this cross section are unsuitable.

Cross section named as a “Triangle 1” is the best to use for larger spans. When the length of lamella with the cross section “Triangle 1” is longer than 3.2 m, there should not be risk of transverse resonant vibration caused by Von Karman vortex street.

As well as these, other analyzed cross sections have their pros and cons and they can be used with respect to above mentioned principles.

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