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Dynamic Loading of Feyenoord Stadium during pop concerts

Sollicitation dynamique du stade de Feyenoord lors de concerts

Dynamische Belastung des Feyenoord-Stadiums bei Pop-Konzerten

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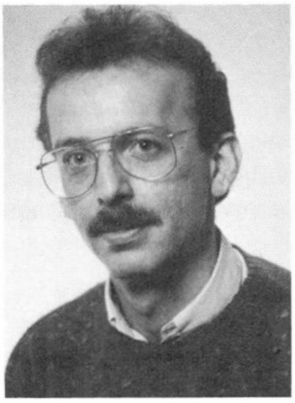

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SUMMARY

Since 1980, the Feyenoord football stadium is also used as a venue for pop concerts. During the concerts large vibrations sometimes appear in the structure as a result of dynamic crowd loading. During pop concerts the structure is being monitored. With the monitored data a direct feedback can be given to the sound and video director. Based on this feedback, they interfere with sound and video and can thus limit the vibrations. With this system experience has been gained during 25 concerts, covering a period of 5 years.

RÉSUMÉ

Depuis 1980 le stade de football de Feyenoord sert aussi pour les concerts de musique populaire. D'importantes vibrations des structures porteuses furent constatées au cours de ces concerts, par suite de l'action dynamique des mouvements de foule. Dès lors, un système de mesure surveille la structure et les données relevées sont directement transmises aux responsables son et lumière. Ceux-ci peuvent réduire les performances acoustiques et ainsi limiter les vibrations. Le système a été expérimenté pendant 5 ans et 25 concerts.

ZUSAMMENFASSUNG

Das Feyenoord Fussballstadion wird seit 1980 auch für Pop-Konzerte benutzt. Mitunter machen sich grosse Tragwerksschwingungen als Folge dynamischer Einwirkung von Menschenmassen bemerkbar. Das Tragwerk wird jetzt während Pop-Konzerten messtechnisch überwacht und die Messdaten direkt den Licht- und Ton-Meister überspielt. Letztere können das Klangvolumen dämpfen und dadurch die Schwingungen begrenzen. Es wurden während fünf Jahren bei 25 Konzerten Erfahrungen gesammelt.

1. INTRODUCTION

The Feyenoord stadium had an original capacity of 61.000 people. The stadium consists of two rings that are supported by 120 steel framed trusses placed arond the pitch. The stands are cast-in-place concrete slabs. The second ring of the stadium cantilevers above the first ring in order to obtain a maximum sight on the pitch. The design of this stadium is special, since it gives an unrestricted view on the pitch from every seat of the stadium. Only a part of the second ring has a roof, that is also a cantilever structure. Figure 1 gives a schematic cross section over stands. As can be seen from figure 1, the second ring is as near to the pitch as the first ring, which also contributes to the good sight and gives this stadium some intimacy.

In the design self-weight, static crowd loading and wind load was accounted for. At the completion of the building stage in 1936, a static test loading was carried out by 1500 people. Only one of 120 trusses of the stadium was covered by this loading. Displacements of the first and second ring were recorded. Over the years it has become a well known phenomenon that a goal during a football game yields a well perceptable vibration in the stadium. However, at a football match, this vibration damps out rather quickly. Measurements indicated that the amplitude of the dynamic displacement at such an event, measured at the very extreme of the second ring, amounts to some 2 or 3 mm. In 1987 the stadium design calculations were reviewed on the basis of the vigilating building regulations in the Netherlands. This implied a static crowd loading of 4 kN/m^2 and a wind load having a dynamic pressure of approx. 900 N/m^2. Only minor structural modifications had to be made in order to meet these new requirements.

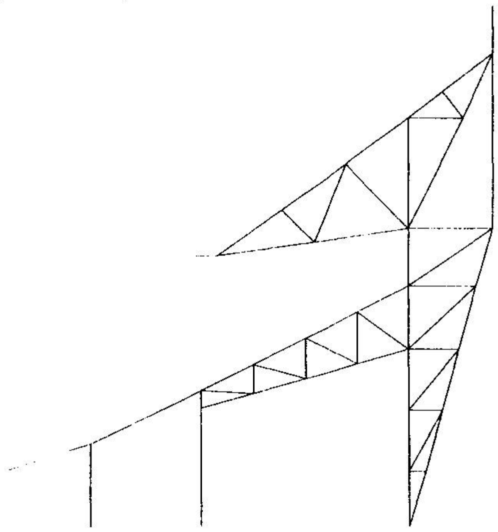

Fig. 1 2D Model of single truss

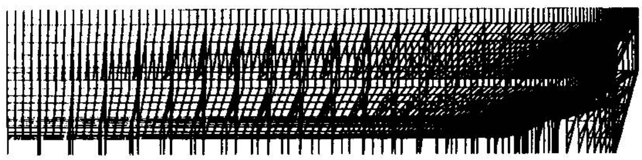

Fig. 2 3-D Model of a quarter of the stadium

2. DYNAMIC BEHAVIOUR DUE TO CROWD LOADING

From the calculations, it appears that the deflection of the second ring due to the static load of 4 kN/m^2 is approx. (25 mm). Such deflections clearly indicate the large flexibility of the structure. This flexibility originates from the special design principles that the architects adopted. An analysis of a single truss using the finite element method DIANA shows that the first three natural frequencies of a single truss are below 10 Hz. Also a quarter of the perimeter of the stadium (30 trusses) was modeled in order to investigate ring effects. Figure 2 shows the finite element model and results are summarized in Table 1.

frequency (Hz)			mode shape
calc[1]	calc[2]	meas	
1.58	2.02	2.3	predominant lateral sway of the second ring
3.65	-	4.5	predominant out of plane translation of the second ring
6.14	-	5.8	predominant vertical translation of the tip of the first ring

Table 1 Natural frequencies and mode-shapes of the stadium structure
[1]) analysis of single truss (2D model); [2]) analysis of a quarter of the perimeter (3D model)

In figure 3 the mode shapes of a single truss are shown. In 1982 vibrations measurements with just wind as excitation confirmed the existence of these natural frequencies. The estimated damping ratios (as a fraction of the critical damping) are approx. 0.07, 0.12 and 0.05 respectively. From the calculations and measurements it can be concluded that the additional stiffness of ring-shaped concrete slabs is significant.

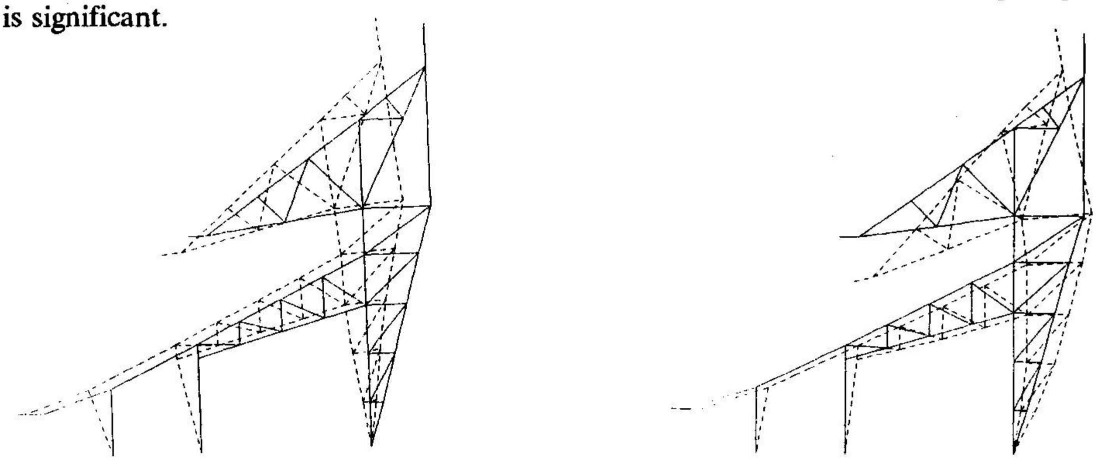

Fig. 3 First two mode shapes of a single truss

Dancing people can exert a significant dynamic loading at frequencies of around 2, 4 and 6 Hz. Indeed, at the first pop concerts that were organised in the stadium strong vibrations did occur. At the second ring the vibration intensity was such that some people got frightened. The city authorities responsible for building safety ordered an investigation into the extent and causes of these strong vibrations.

3. MODELS OF DYNAMIC CROWD LOADING

The main dynamic loading during pop concerts are due to dancing or bending of the knees, on the rhythm of the music. Different models for this loading have been proposed in literature, such as the sine model, and the triangular model. Since we deal with a periodic excitation, it can be developed into a Fourier series

$$F(t) = G[1 + \sum_n \alpha_n \sin(2\pi f_n t + \phi_n)]$$

where
G is the weight of the people, in N
α_n is the fourier coefficient for the n-th harmonic, normalized on G
f_n is the n-th harmonic frequency, in Hz
ϕ_n is the phase of the n-th harmonic, in rad

Table 2 gives a set of Fourier coefficients for different models with $f_1 = 2$ Hz as found in literature.

model	α_1	α_2	α_3	remarks
uniform model	1.65	0.83	-	(t_c /t = 0.33 after Wyatt [10])
sine model	1.78	1.26	0.63	(t_c /T = 0.34 after Eibl [4]
triangle model	1.62	0.81	0.18	(t_c /T = 0.5 after Gerasch [5])
measured	1,80	1.31	0.75	(t_c /T = 0.4, after Baumann [2])
measured	1,46	0.60	0.17	(N persons, after Embrahimpour [3])
measured	1.65	0.90	0.25	(1 person, after Allen [1])
measured	1.45	0.50	0.07	(8 persons, after Pernica [7])
measured	-	0.51	0.10	(building measurement, after Rebelo [8])

Table 2 Fourier coefficients for dynamic crowd loading

As shown by Pernica [7], the sine and triangle model appear to be conservative for the 2nd and 3rd harmonic, especially for groups of people. Probably small differences in dancing between individual people tend to decline these coefficients. The lower values for the 2nd and 3rd harmonic are confirmed by measurements in buildings reported by Rebelo [8]. The decline of the fourier coefficients for a higher number of people is also indicated by Kasperski [6], who introduces a coordination factor in order to account for this. For large groups, this factor is stated to be 0.5.

The data above show that for a purely static structure, the action effect due to dynamic crowd loading is 2 to 3 times the static crowd loading. The coincidence of forced and natural frequencies, as may well be the case in the Feyenoord stadium, will even increase this ratio due to resonance effects.

Under unfavourable conditions such as a strongly correlated dynamic loading and a coincidence with one of the natural frequencies, these theoretical considerations imply that dynamic crowd loading in the Feyenoord Stadium may lead to very large dynamic displacement and stress amplitudes. Such a dynamic response may be unacceptable both from the point of view of building safety and vibrational discomfort. The uncertainty in the dynamic response to pop concerts forced the city authorities in 1987 to withdraw the permit for pop concerts in the stadium. Only a limited permit was issued only for a few concerts to allow for measurements to be made.

4. MEASUREMENT OF THE DYNAMIC CROWD LOADING

In August 1987 additional measurements into the dynamic behaviour of the stadium were performed during the concert of Madonna. At approximately 1/4 of the perimeter of the second ring of the stadium the vertical acceleration was measured, see Figure 4. In addition to this, strains were measured at a number of critical elements in several trusses. The maximum amplitudes amount to 3 mm vertical and 2 mm horizontal. Accelerations reached peak values of 1,3 m/s^2.

Transfer functions were calculated between the deflections measured at different places along the second ring. From this, figure 4 shows the ratio of the displacement at 2 and 4 Hz along the second ring, together with the phase lag. Due to the fact that the sound arrives later at a greater distance, a considerable phase lag occurs. This leads to a kind of 'wave' in the structure.

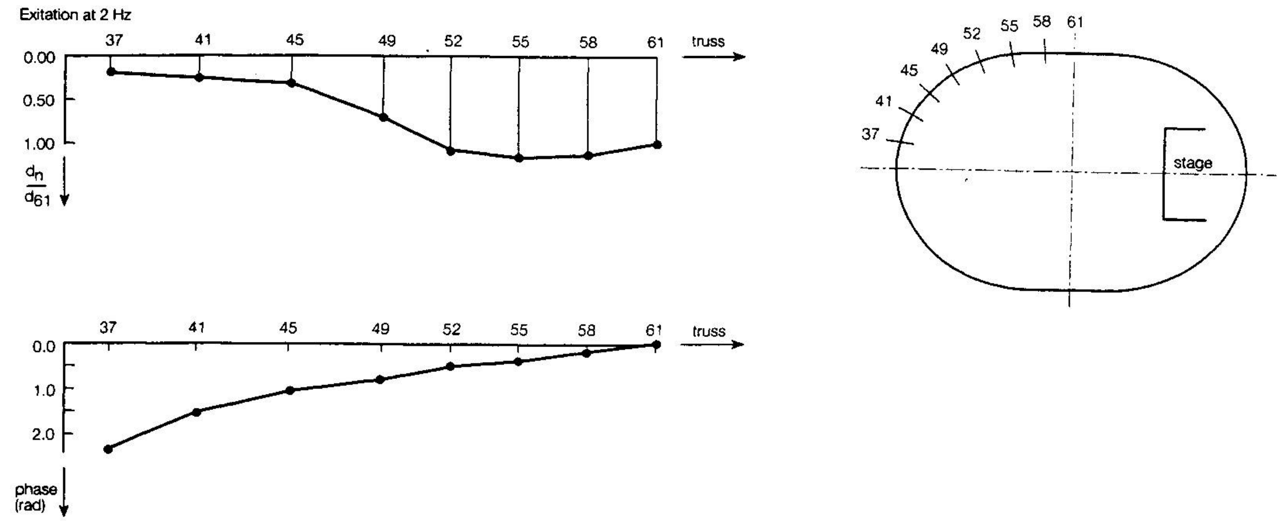

Fig. 4 Ratio of displacement along the perimeter of the stadium at 2 Hz

The static displacement of the 2nd ring is approx. 10 mm; at this concert the static crowd loading appeared to be 1.7 kN/m^2 and the maximum dynamic amplification 1.3. The relation between deflection and strain at 2 and 4 Hz differs from the static relation, indicating that vibration modes also play an important role. Especially the 2.5 Hz lateral sway induces a remarkably small strain in the main vertical truss.

5. MONITORING OF VIBRATIONS

In 1987 it was decided that additional measures must be taken. Structural modification appeared to be very difficult due to the specific design of the stadium. Also, the installation of dampers was not favourable due to costs and the uncertainty about their effectiveness. Therefore, the priority was set on a monitoring system with direct feedback to the pop concert, since this could be installed at short time and moderate cost.

The monitoring of dynamic effects caused by some 50000 people requires a dedicated system having a very small response time with regard to the feedback. Based on the extensive measurements in August 1987 five locations along the 2nd ring were selected. Here, transducers were installed for measuring the horizontal and vertical deflection of the second ring. During concerts, these displacements (both static and dynamic) are continuously measured and evaluated, using a PC-based measuring system.

The feedback consist of a warning system to the sound and video directors of the concert. At prescribed levels of vibration, starting at 4 mm the sound level has to be lowered stepwise until a complete close-down at 6 mm, which in practice means an allowable dynamic amplification of 1.6. At an early stage, video screens have to show a neutral view. Experience has learned that at the moment the sound is lowered and closed down, the coherent excitation by the crowd stops within a few seconds.

Ideally, a fully automatic system could have been installed, that makes its decision on the basis of the measured results and can lower or switch off the sound level automatically. Because of the sensitivity of such a system for possible disturbances in the measuring signals or otherwise and problems of acceptation by promoters, two human decision makers are part of the chain:

the operator of the measuring system (the system however will indicate what action must

indicated to the sound and video director),
the sound and video directors of the artist concerned.

An additional advantage is that a permanent communication channel between stadium authorities and sound and video director exists.

Contracts between stadium and promoters for organizing concerts imply these procedures as conditions. Furthermore, the City of Rotterdam based its permit for organizing pop concerts in the stadium on this system.

6. EXPERIENCE

As far as known, this kind of monitoring system has not been applied earlier in order to insure the structural safety of a stadium under dynamic loading. For this reason, some experiences gained at the operation of this system are discussed here.

All concerts in the Feyenoord stadium since 1988 have been run using this system. Among these are concerts by Bruce Springsteen, The Rolling Stones, Genesis, Guns 'n' Roses, U2 and Metallica. Approximately 1 million visitors were present in this 5 year period. Apart from small modifications and software updates, the basis of the system is still the same as originally designed.

Prior to concerts a meeting is set with stadium officials, the promoter, the tour director, the sound and video director and the people concerned with the monitoring. After any concert, the results are made available for city authorities. Many concerts could be run without interference in the concert from the point of view of vibrations. During some concerts the sound level had to be lowered in preparation for a the complete switch-off. So far, only at the Guns 'n' Roses concert in 1992 sound nearly had to be switched off. This implies that the dynamic amplification rarely exceeds 1.6 and that the value of the coordination factor will be lower than 0.5.

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