VIBRATION OF FOOTBRIDGES UNDER PEDESTRIAN LOADS

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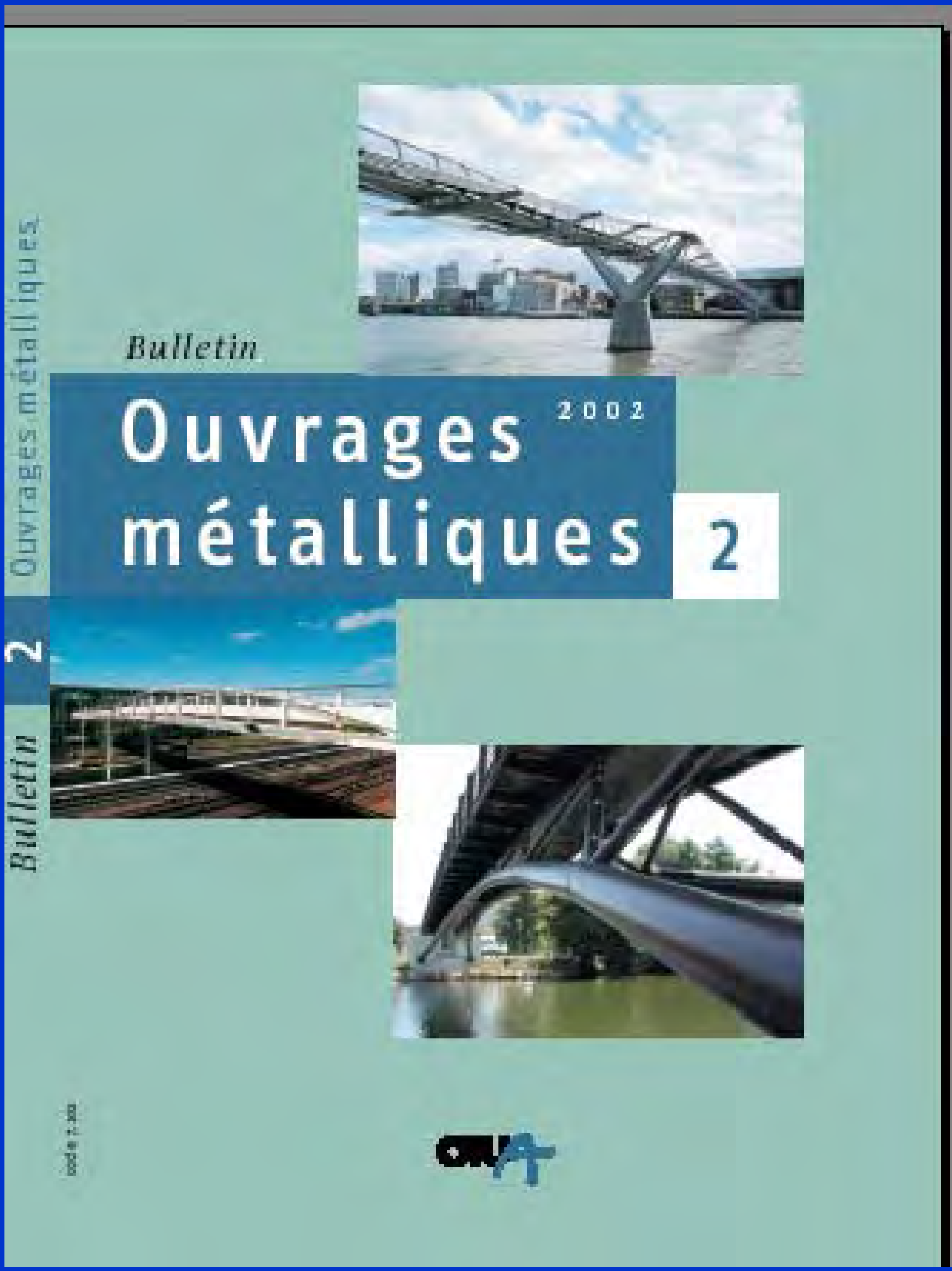
FRANCE

Solférino Footbridge Opening and Closure in 1999

WG on Footbridge Pedestrian Dynamics in 2000

FOOTBRIDGE MAGAZINES

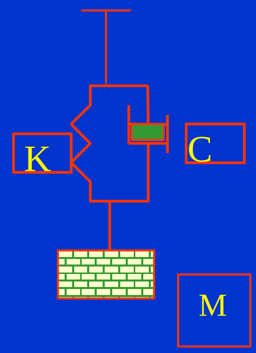


VIBRATION OF FOOTBRIDGES UNDER PEDESTRIAN LOADS

SUMMARY

- 1 - DYNAMIC ACTION
- 2 - PEDESTRIAN LOADS
- 3 - EXAMPLES OF “WOBBLING” FOOTBRIDGES
- 4 - REMEDIES
- 5- RECOMMENDATIONS OF THE FRENCH WG

DYNAMICS OF STRUCTURES



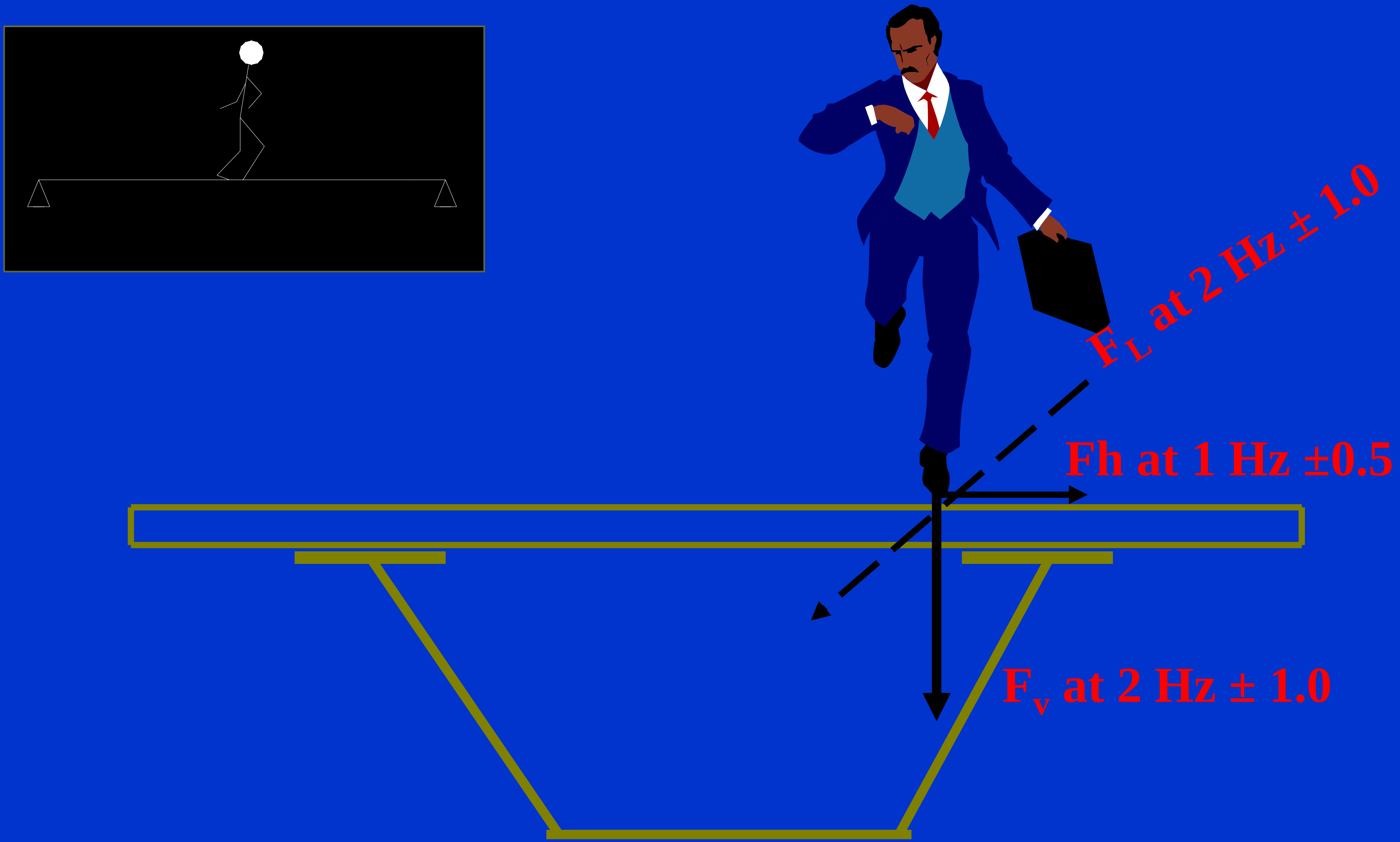
- $$M\frac{d^2U}{dt^2} + C\frac{dU}{dt} \quad KU \quad = F(t)$$

F(t) : Pedestrian Action

F(t) contains all the complexity of humanity. The applied forces are governed by a sophisticated control system : the human brain –

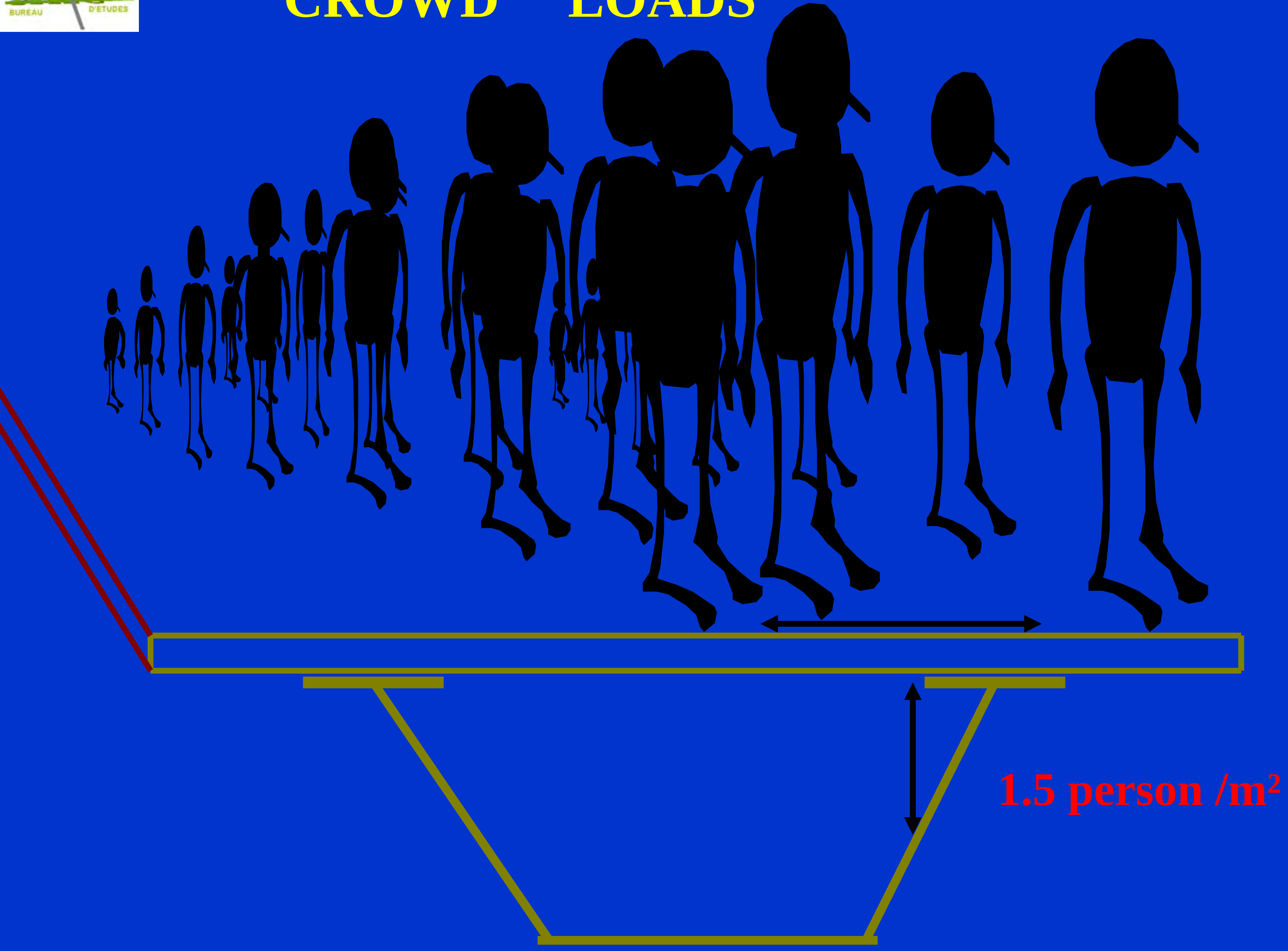
Interaction between the strucutre and the pedestrian

ACTION OF ONE PEDESTRIAN



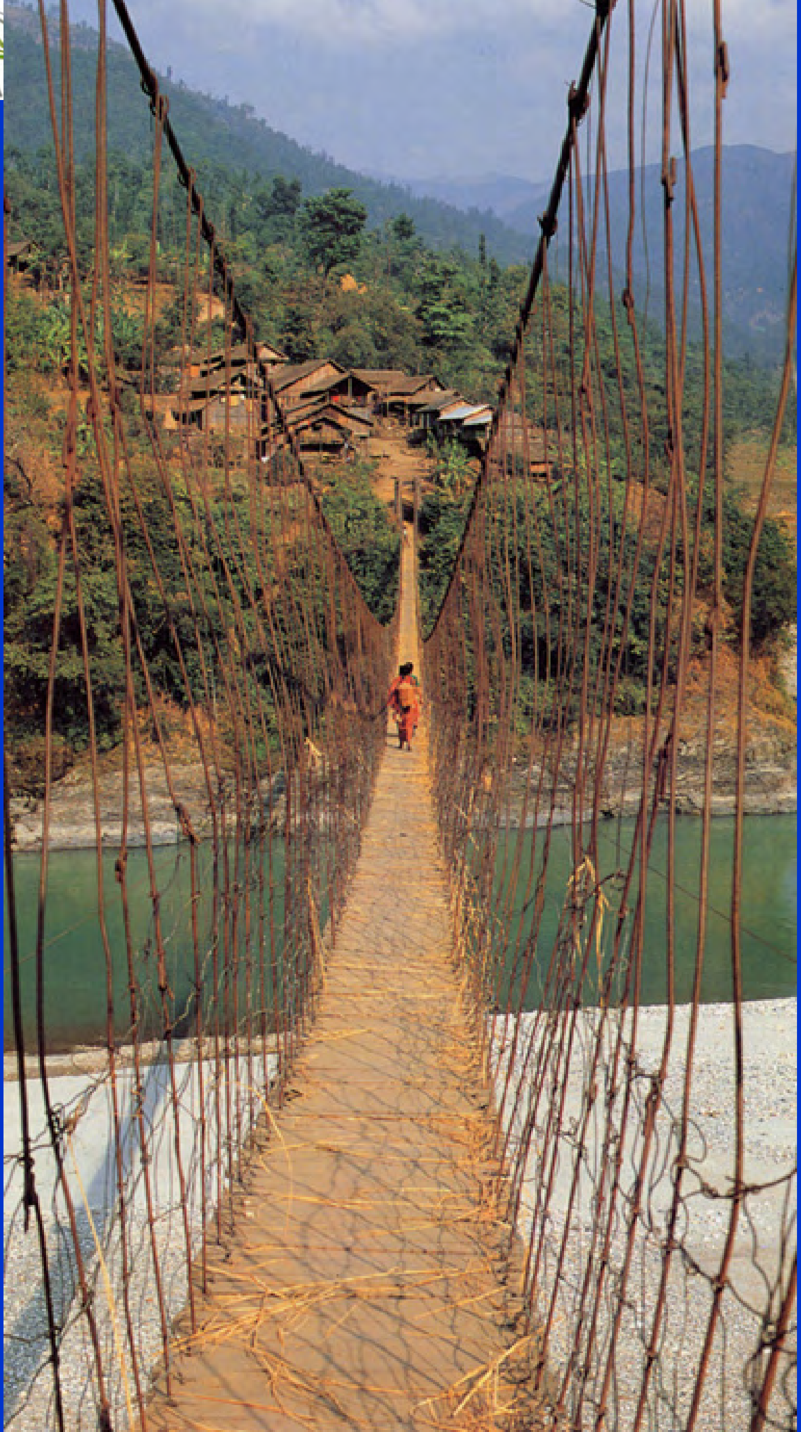
RHYTHMIC ACTIVITIES

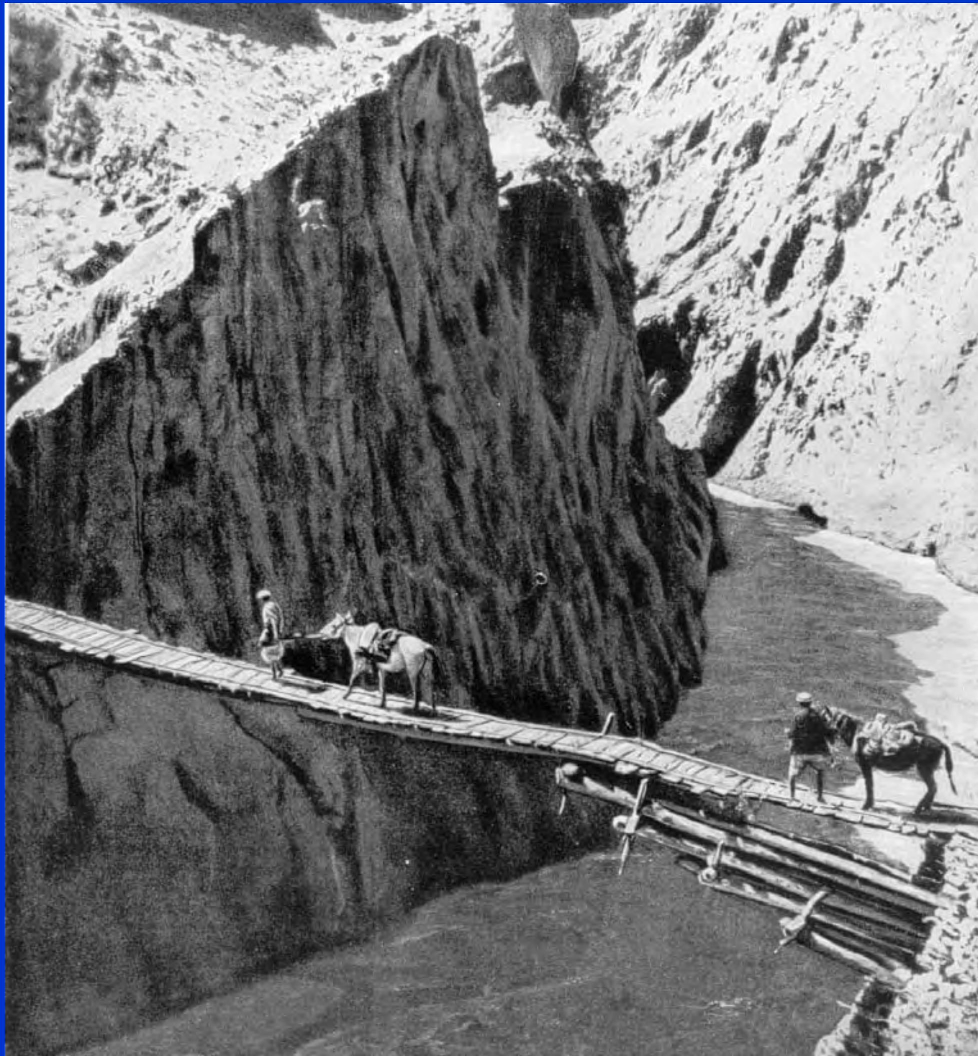
CROWD LOADS



VIBRATIONS

Comfort criteria ?





DYNAMICC ACTION OF PEDESTRIANS

- 95% walk at a frequency between 1,6 and 2,4 Hz and 50% between 1.9 and 2.1 Hz
- Above 5 Hz, vertical modes are unlikely to be excited
- The periodic lateral force has a frequency equal to half of the vertical excitation

VIBRATION OF FOOTBRIDGES UNDER PEDETRIAN LOADS

	total range	slow	normal	fast
walking	1.4 – 2.4	1.4 – 1.7	1.7 – 2.2	2.2 – 2.4
running	1.9 – 3.3	1.9 – 2.2	2.2 – 2.7	2.7 – 3.3
jumping	1.3 – 3.4	1.3 – 1.9	1.9 – 3.0	3.0 – 3.4

H.BACHMANN

Table 1 Pacing and jumping frequencies in Hz
VERTICAL

Single pedestrian

General load

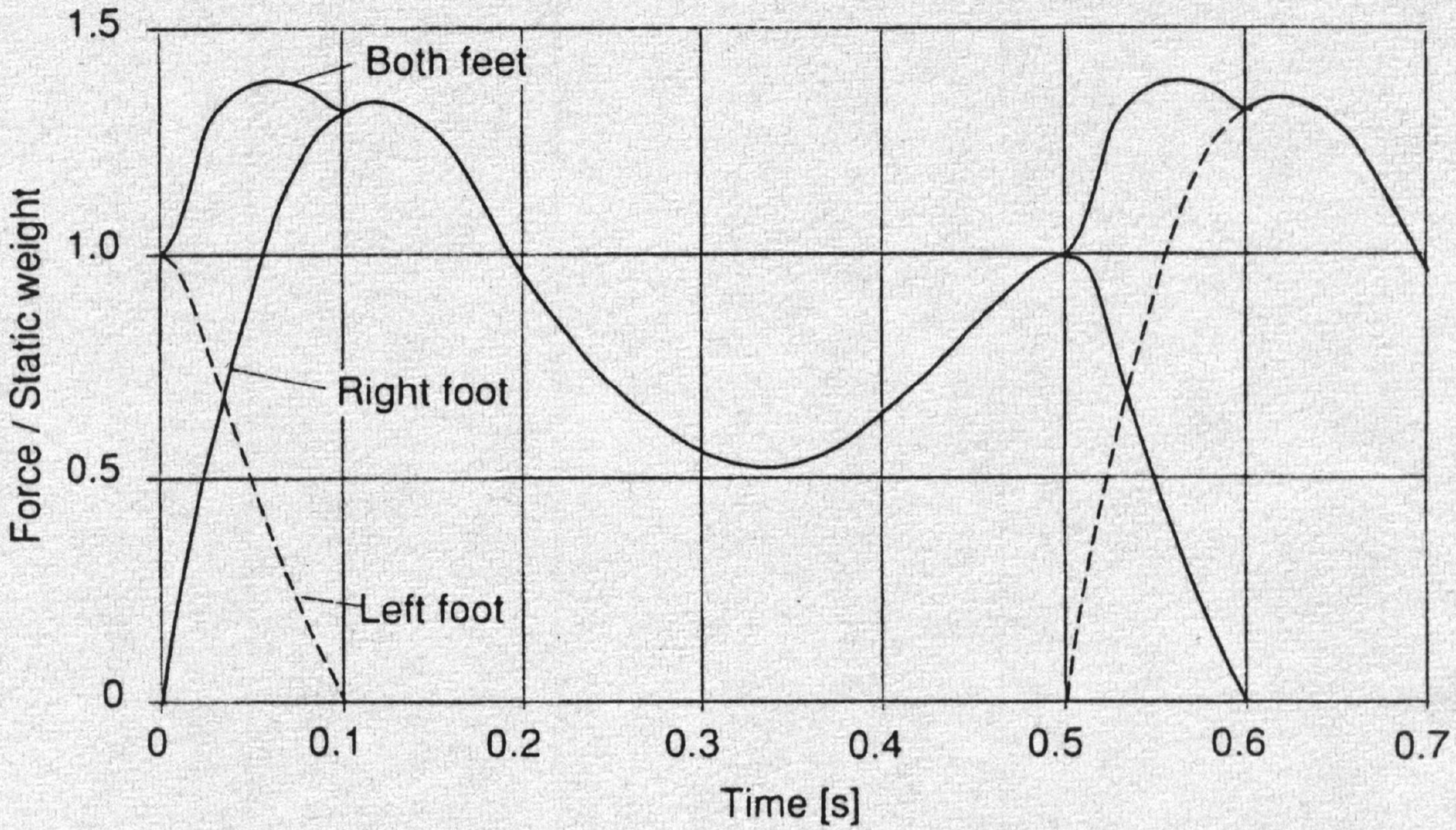
$$P(x,t) = P(t)\delta(x - vt)$$

with:

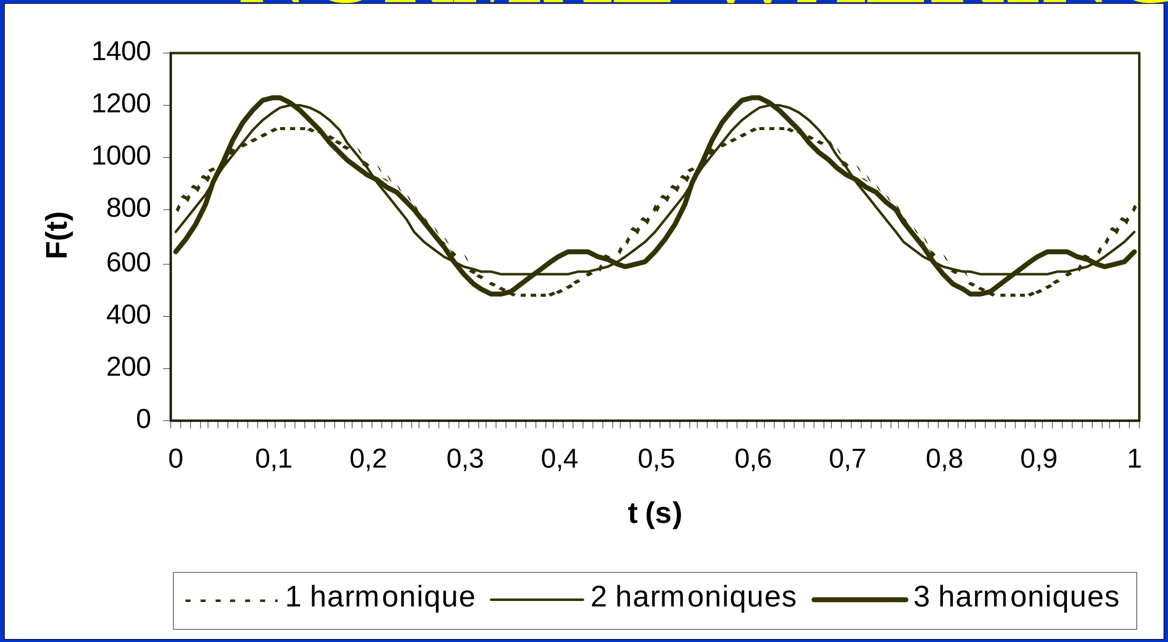
$$P(t) = P\left[1 + \sum_{k=1}^{\infty} \alpha_k \sin(k\omega t - \varphi_k)\right]$$

Fourier coefficient	α_1	α_2	α_3
Walking (vertical)	0.40-0.56	0.1-0.28	0.1-0.12
Running	1.2-1.6	0.1-0.47	0.1-0.20

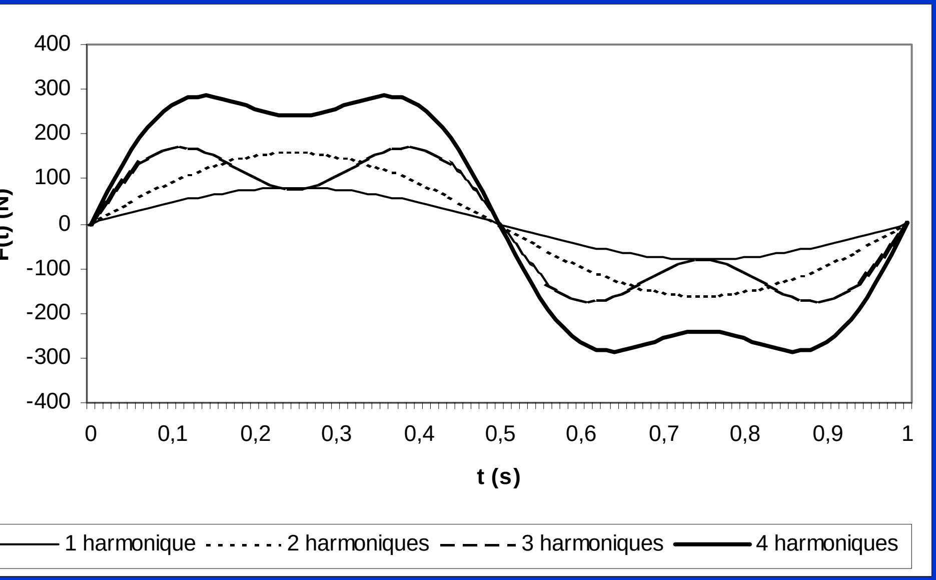
PEDESTRIAN LOAD FUNCTION

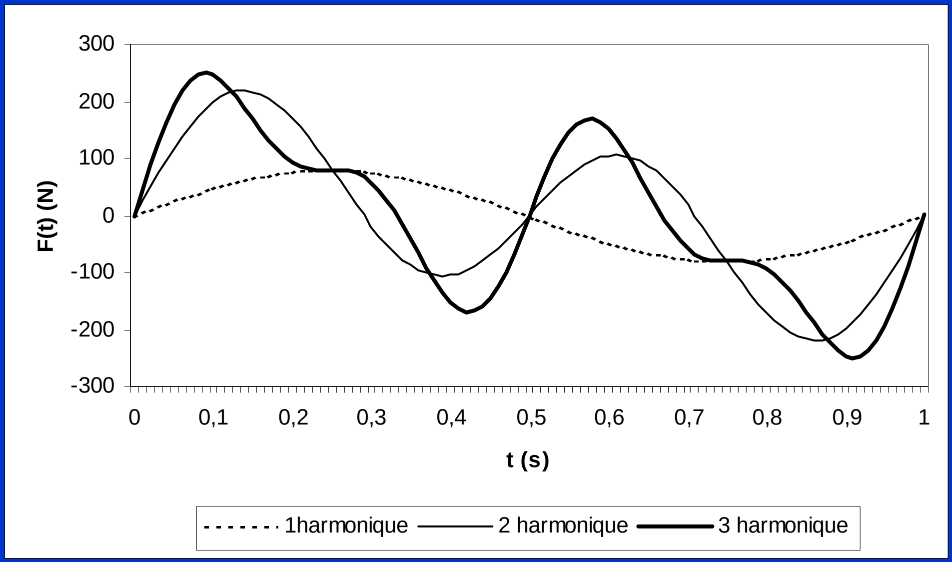


NORMAL WALKING



Vertical





LATERAL

LONGITUDINAL

Pedestrian load EC5-2

General load

$$P(x,t) = P(t)\delta(x - vt)$$

EC5-2

$$F = 280\sin(2\pi f_0 t)$$

280 = 0,4 x 700

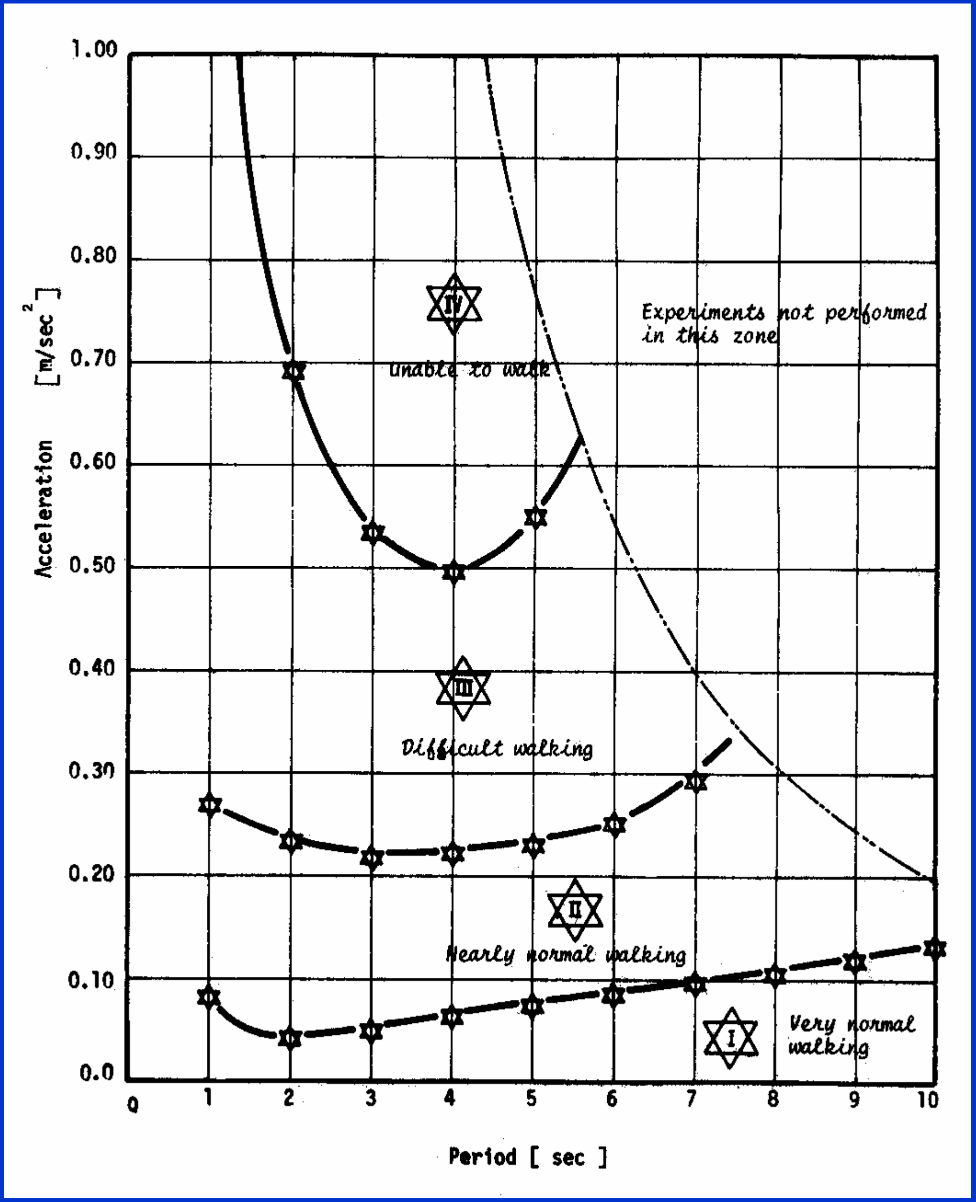
Moving speed

$$v = 0.9 f_0$$

Comfort

- The comfort feeling depends on each individual. Some person are very sensible, others not at all. Some get used to the discomfort quickly
  - Feeling of danger in case of large displacement
  - Sea sick in case of high acceleration .
- For designers, the comfort criteria is measured by the deck acceleration.

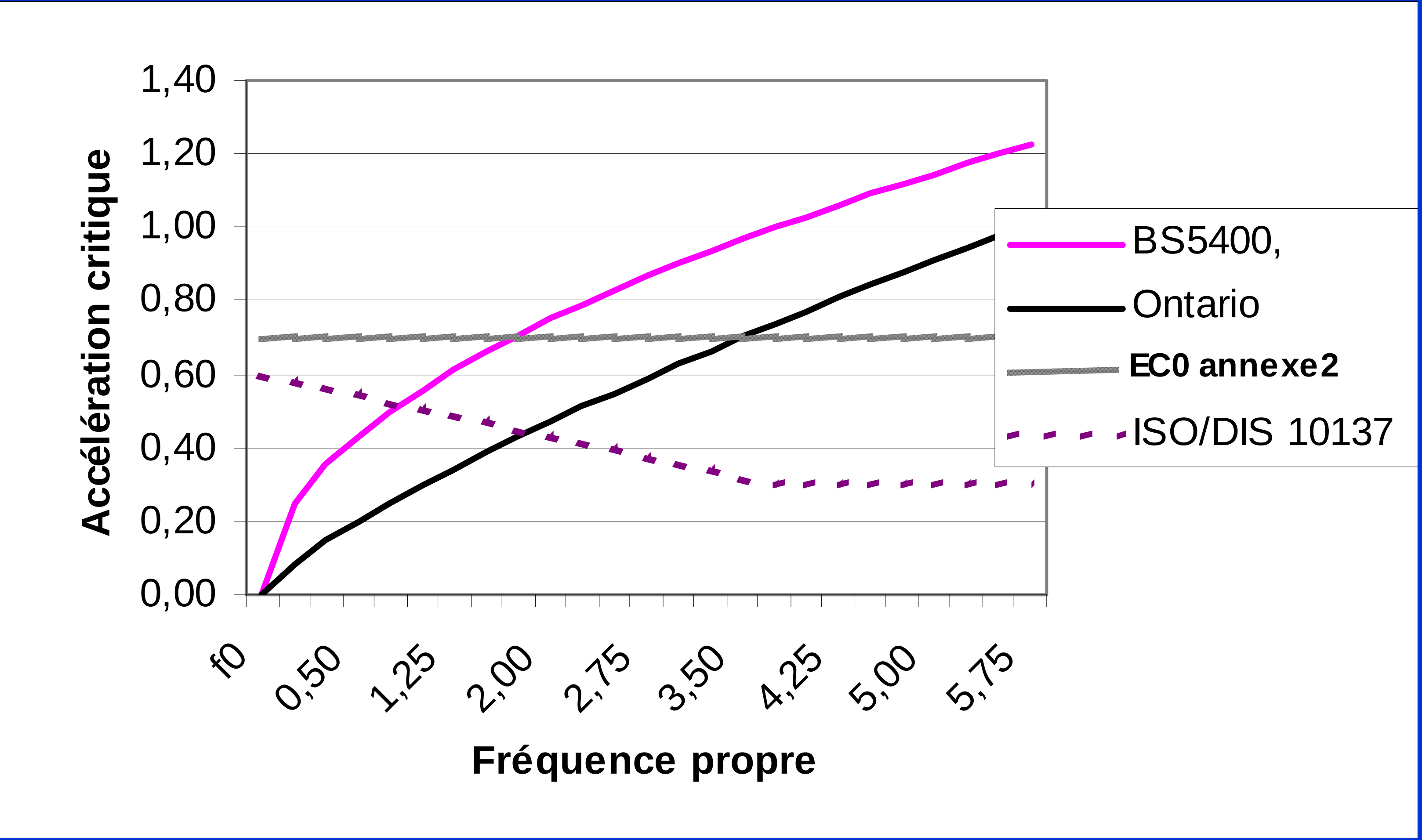
Effect of lateral vibration on ability to walk



Acceleration /comfort criteria

- Vertical Accélération : 0,5 à 0,7 m/s²
- Horizontal acceleration : 0,15 m/s²
- Difference between vertical et and horizontal oscillations:
  - Vertical oscillation rarely hinders walking
  - Horizontally, high acceleration causes unbalance of pedestrian equilibrium who must adapt their walk.

Acceleration Limits



CROWD LOADS

- The regulations and standards do not clearly define crowd loads but rather the resulting effects.
- A group of pedestrian walk in a Gaussian distribution phase

$$a_{\max,n} = \sqrt{n}\, a_{\max}$$

- Experimental observation (Fujino - horizontal)

$$a_{\max,n} = 0.2\, n\, a_{\max}$$

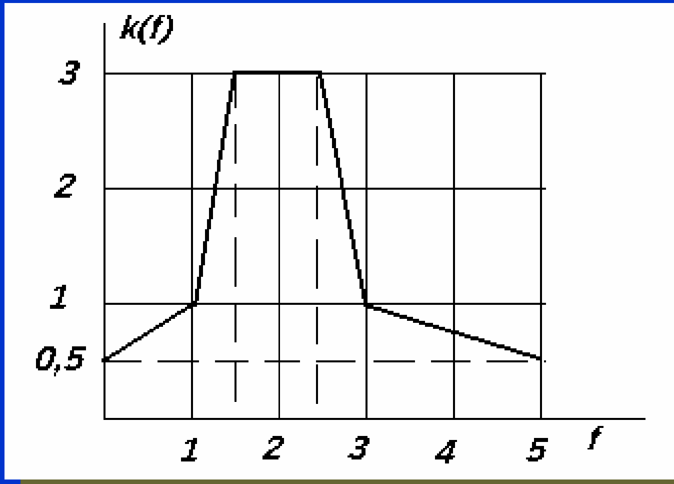
Crowd loads
Complex structures

- For simple structures, the previous approach was sufficient.
- For very large, slender and complex structures, it is not realistic. For example for a crowd of 1000 people, the two values are different.
- A special crowd load is necessary to evaluate the response of such structures, by including torsionnal and horizontal modes.
- Special opening day crowds!!

EUROCODES PROPOSAL

- Proposal for EC1
- Two load models
  - Small group (not necessary for single pedestrian)

$$F_n = 280k(f)\sin(2\pi f t)$$



  - Crowd loading ()

$$F_s = 15k(f)\sin(2\pi f t)$$

NEED FOR RESEARCH

- Crowd loadings are not well known :
  - Real in situ experimentation
  - Numerical simulation
  - Abnormal excitation : “vandalism”
- Comfort criteria
  - Are acceleration values enough ?

New rules required

Different levels of regulations :

1. Forbid certain frequency range.
2. Calculations and verifications within these intervals.
3. When comfort criteria is not respected, take into account the possible pedestrian traffic on the footbridge.
4. In case of proven discomfort, provide the possibility to add dampers .

5. The self-excited lateral response of footbridges due synchronised pedestrian loading

Vertical direction

- Footfall forces can induce excessive vibration in bridges having vertical frequencies between 1.5Hz to 2.5Hz.

- Bridges having frequencies between 3Hz to 5Hz may be susceptible to 2nd harmonic response.

- Effects of walking groups requires further experimental research
  - Response levels above which synchronisation occurs
  - Effects of pedestrians on damping

Lateral direction

- Any bridge with a lateral mode of natural frequency below 1.3Hz is potentially susceptible to excessive lateral vibration. There is no lower frequency cut-off.
- Large responses will arise if a critical number of pedestrians is exceeded; responses limited by people's ability to continue walking
- The critical number of walking people depends on mass, damping and frequency of the bridge mode
- Very high damping (20%+) may be required to prevent dynamic instability

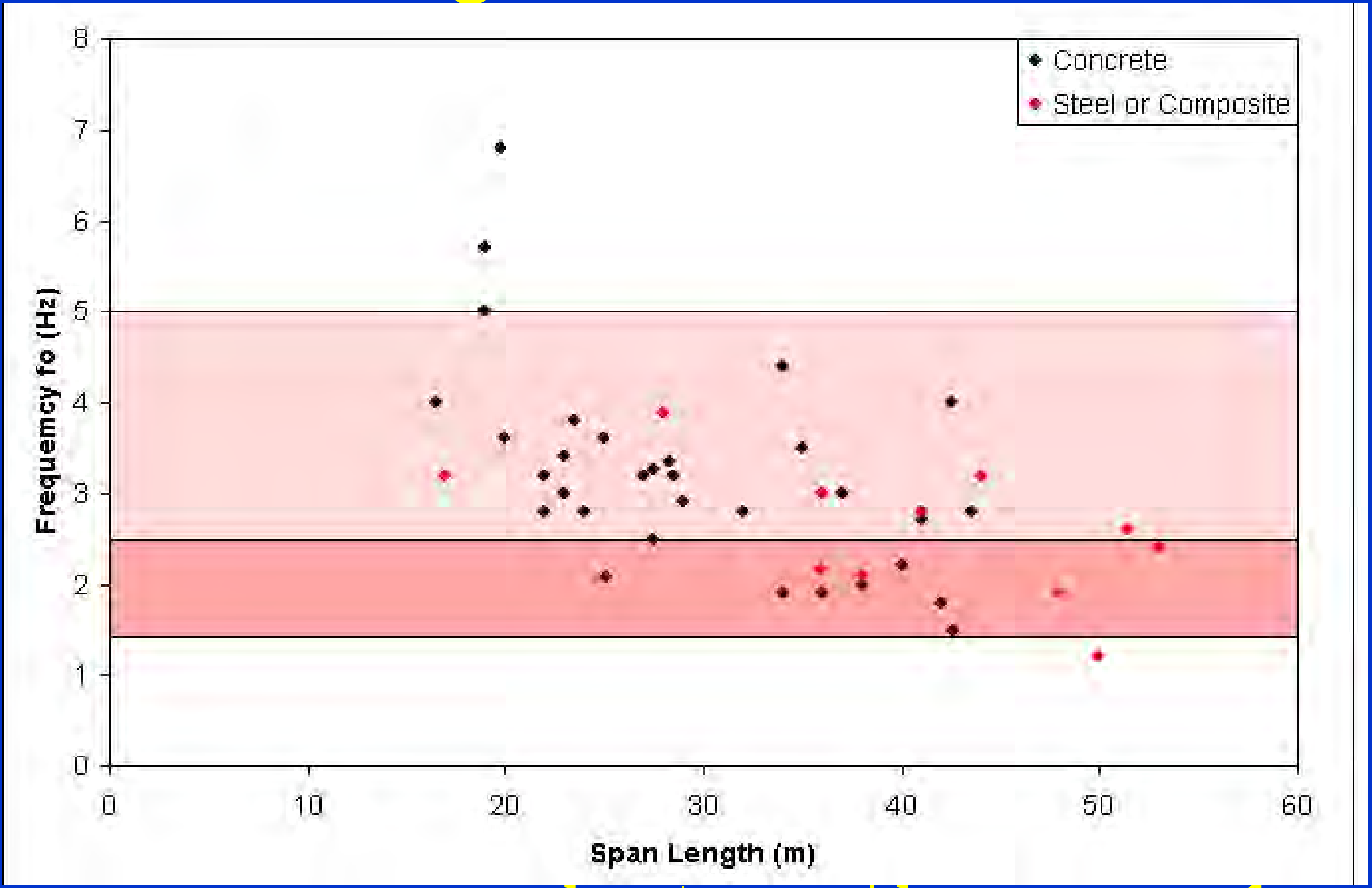
Longitudinal Direction

- To be considered for flexible piers?
- Cable stayed decks?

SOME WOBBLING BRIDGES

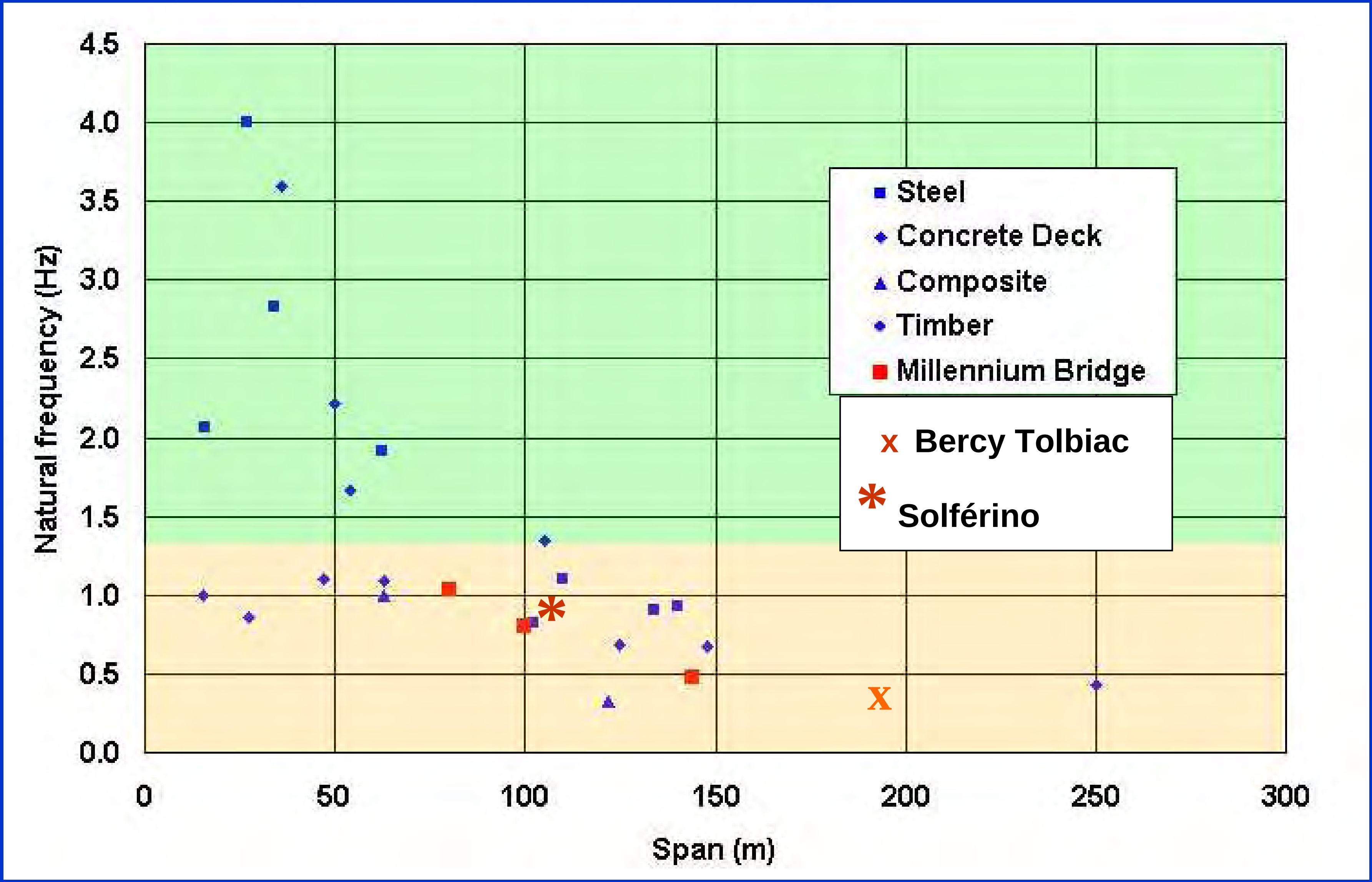
* Problems and solutions

Typical natural frequencies of footbridges: vertical direction



Resonance with 1st or 2nd harmonic of footfall forces

LATERAL FREQUENCY



Passerelle Solférino - Paris

Passerelle Solférino

Tests on site (structure only)

Mode 1	lateral swinging	0.81 Hz
Mode 2	vertical bending 2 waves	1.22 Hz
Mode 3	central torsion + bending	1.59 Hz
Mode 4	vertical bending	1.69 Hz
Mode 5	torsion + swinging	1.94 Hz
Mode 6	central torsion + swinging	2.22 Hz
Mode 7	bending + torsion	3.09 Hz

- Structural damping varies from 0.003 to 0.005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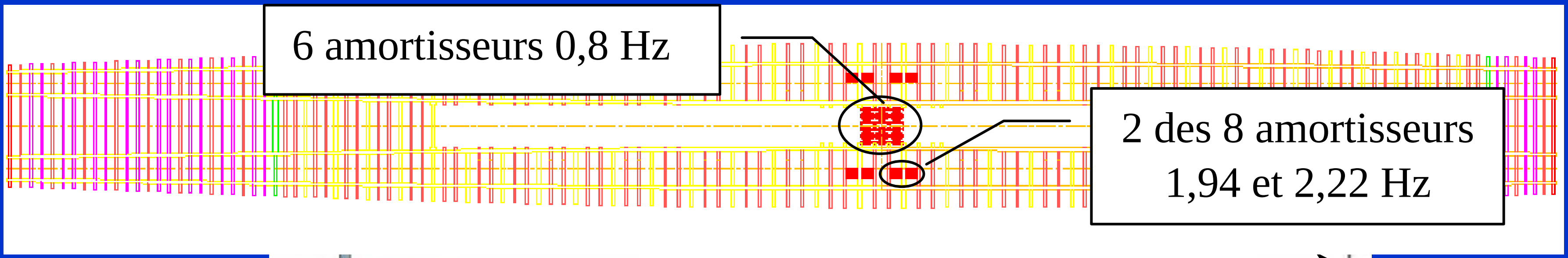
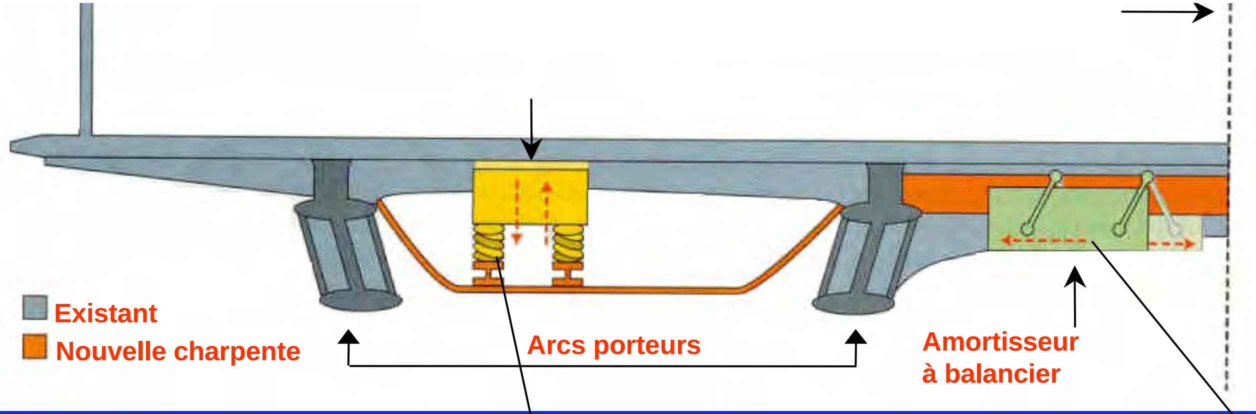
Tuned Mass Dampers (August2000)





Vertical TMD

Double mass spring system

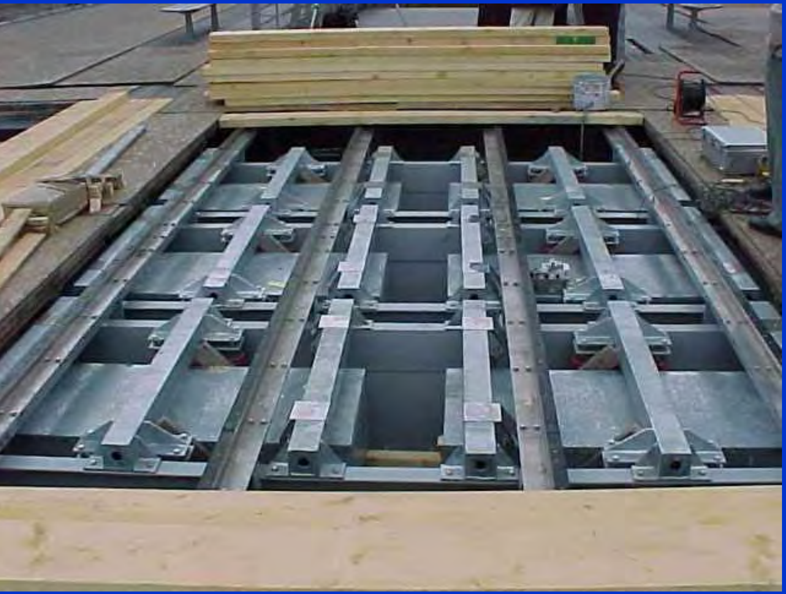
- 2x2 masses 2500 Kg mode 1.94 Hz
  (2,6% generalised mass)
- 2x2 masses 1900 Kg mode 2.22 Hz
  (2,6% generalised mass)

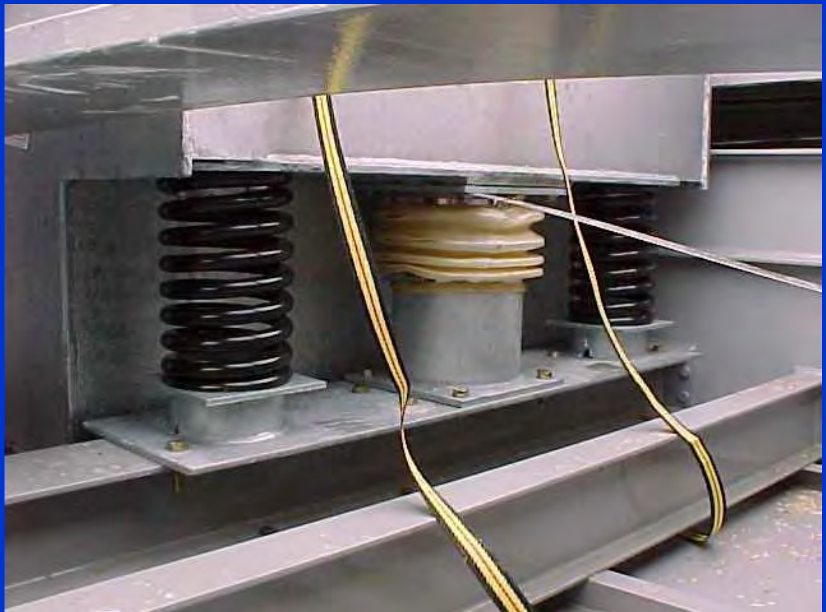
Horizontal Viscous Damper

Pendulum in oil

6 masses 2500 Kg mode 0.8 Hz
bras de levier de 0,5m
(4,7% generalised mass)

Passerelle Solférino – Dampers





Oscillations

MILLENIUM FOOTBRIDGE - LONDON

First lateral frequency : 0,481 Hz

OPENING

AFTER REINFORCEMENT


TCR 00:10:45:22

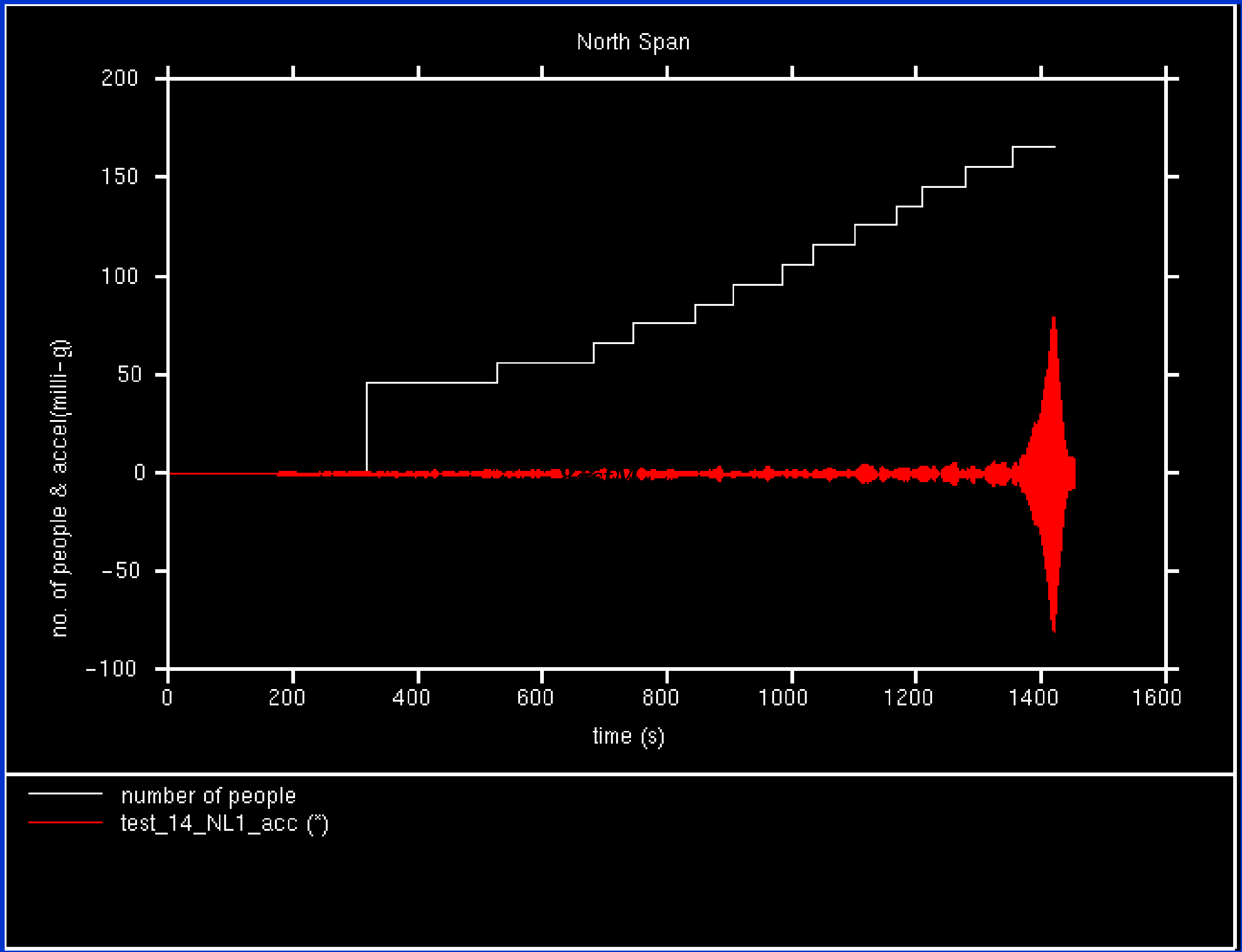
BUREAU D'ETUDES

SYNCHRONISATION TESTS

Imperial College Tests

Crowd tests on bridge

‘Instability’ of lateral response

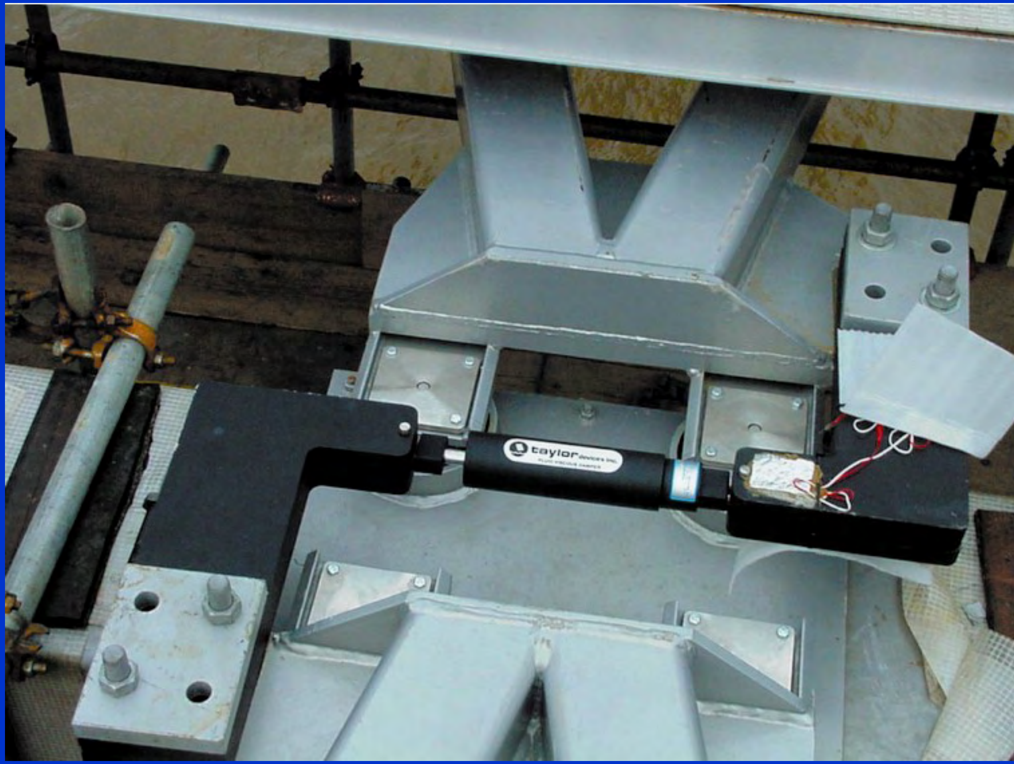


Limiting number of pedestrians : $N \approx \frac{8\pi c f M}{k}$

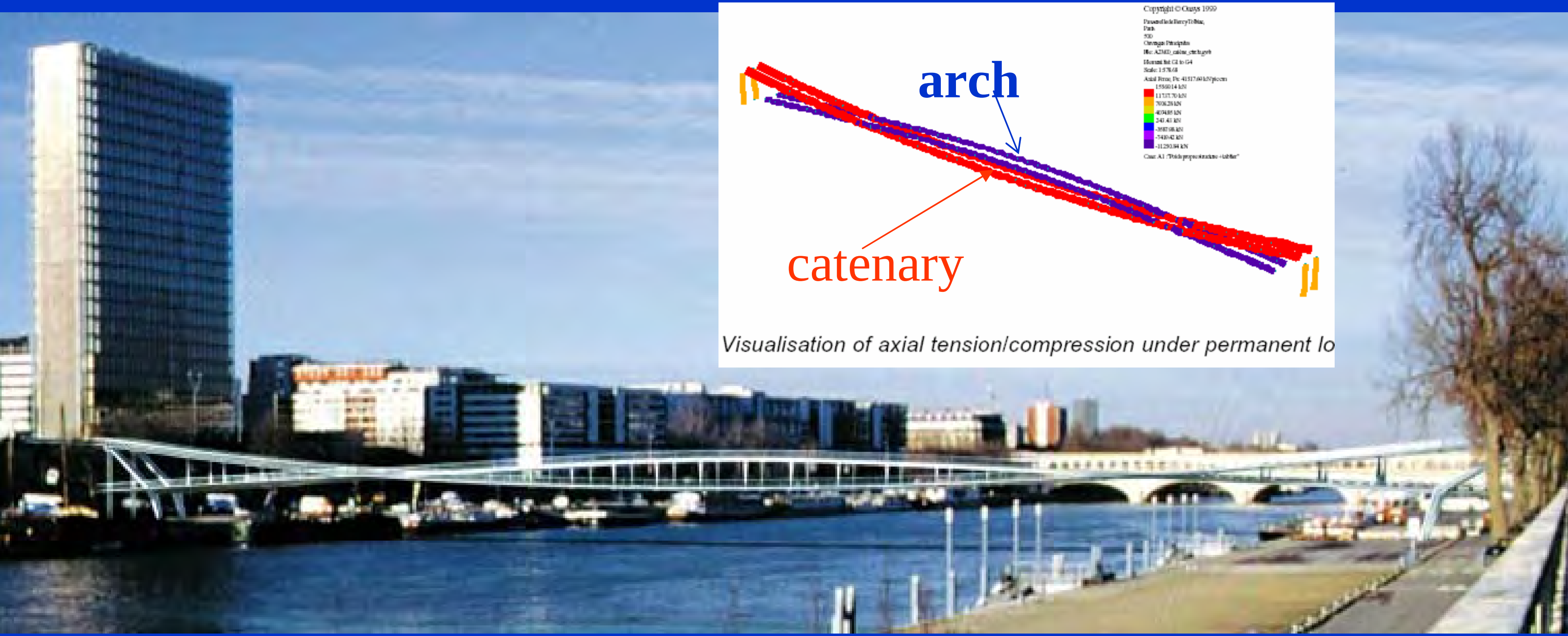
N = 150

DAMPERS

MILLENIUM FOOTBRIDGE - LONDON



PASERELLE DE BERCY TOLBIAC



FEICHTINGER ARCHITECTES

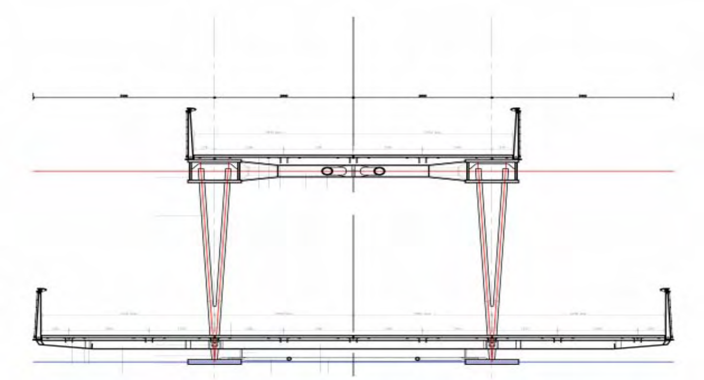
Main span: 190 m

1st horizontal bending: 0.40 Hz
1st vertical bending: 0.67 Hz
1st torsion: 0.95 Hz
(initial project)

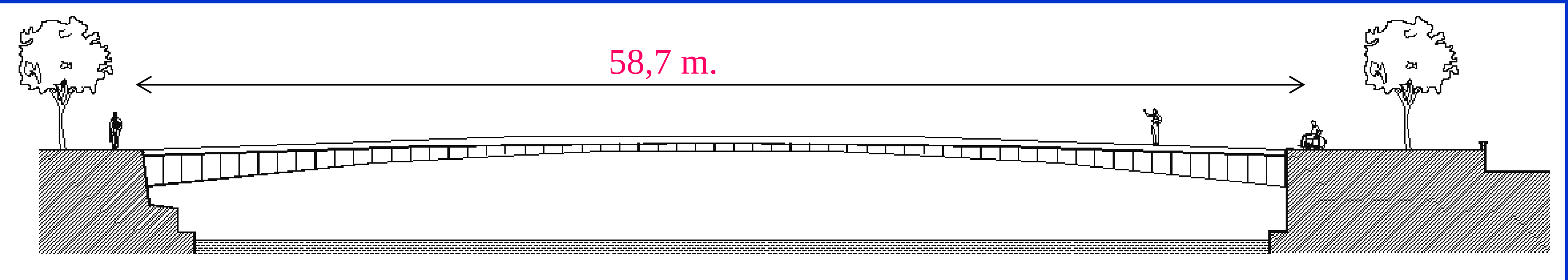
AEROELASTIC INSTABILITY

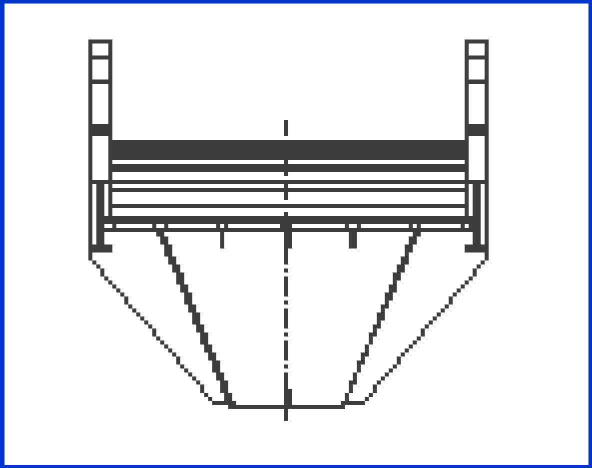
1^{st} horizontal bending: 0.40 Hz
1^{st} vertical bending: 0.67 Hz
1^{st} torsion: 0.95 Hz
(initial project

N = 120



SANT FELIU – GIRONA - SPAIN





FREQUENCY TUNING

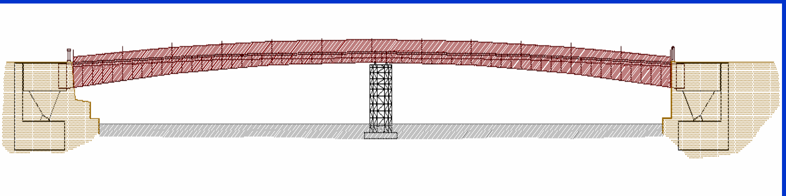
$$f = \lambda \sqrt{\frac{EI}{mL^4}}$$

fo = 2.37 Hz

SANT FELIU
(GIRONA – SPAIN)

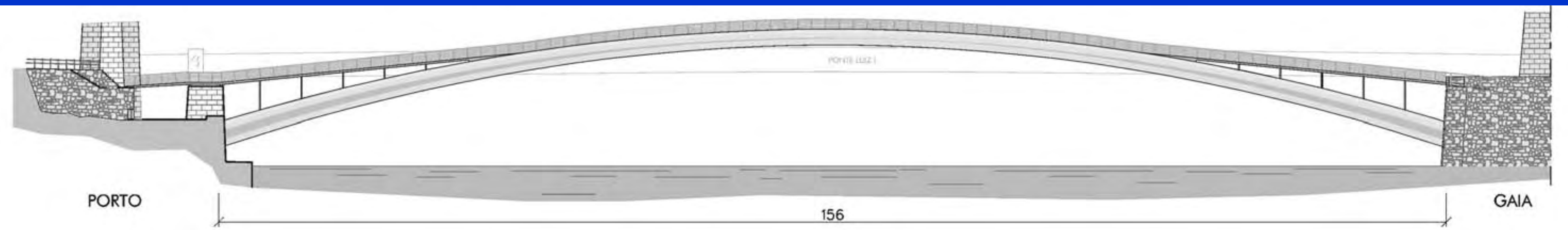
WEATHERING STEEL

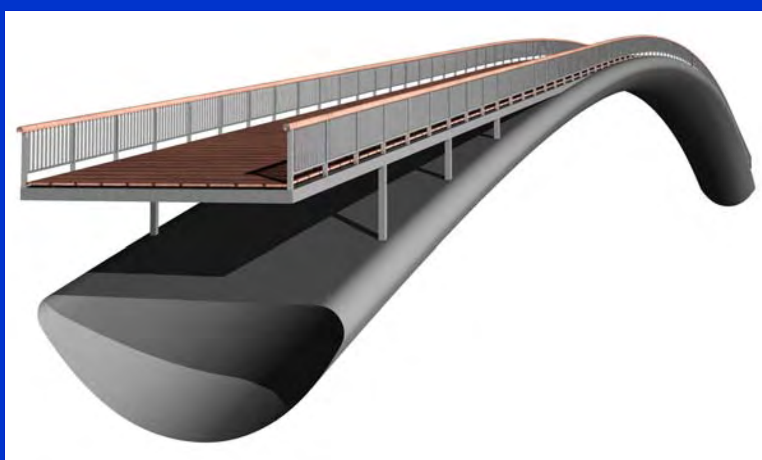
S 355



Wooden roadway surface increases the structural damping

FOOTBRIDGE OVER THE DOURO - PORTO



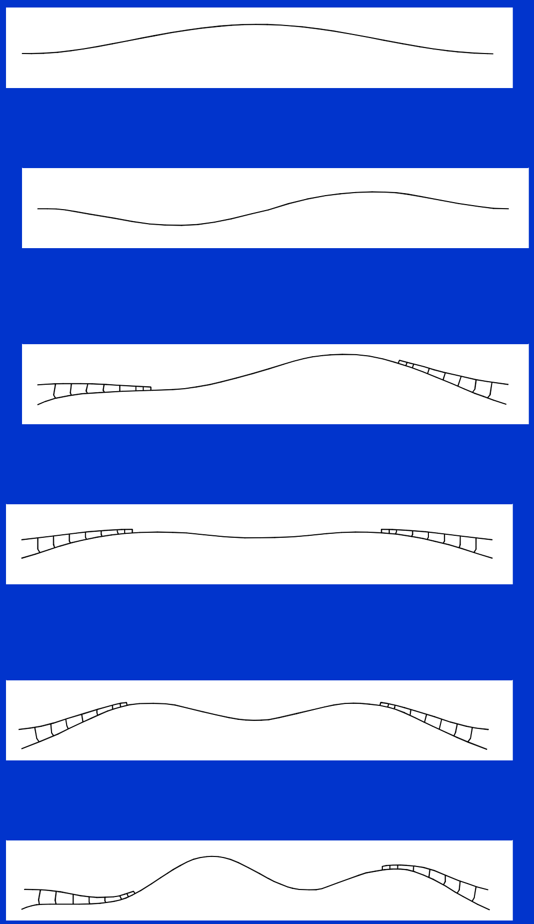


- **STAINLESS STEEL ARCH**
- **HYDRODYNAMIC PROFILE for floods**

FOOTBRIDGE OVER THE DOURO - PORTO

Table 1 Natural frequencies

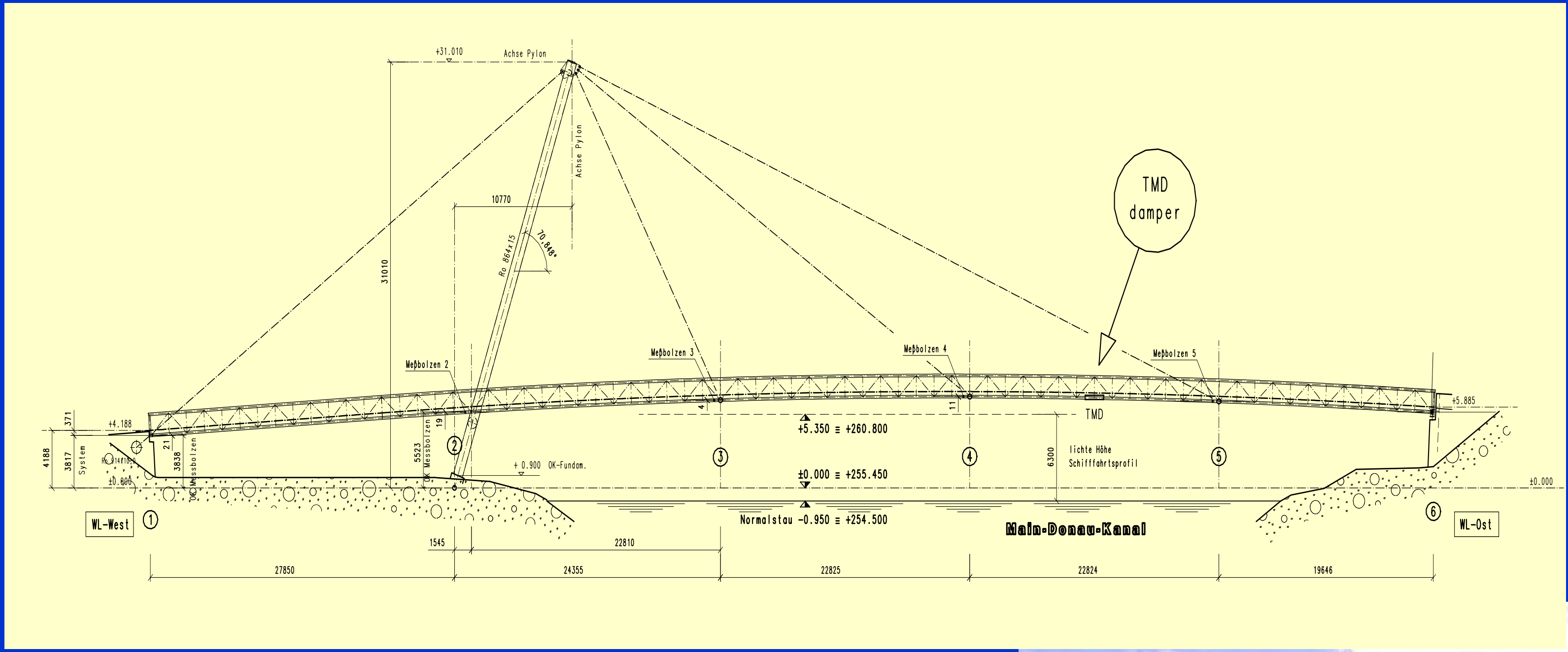
Mode number	Natural frequency (Hz)	Type of mode
1	1.132	1st transversal
2	1.423	1st vertical
3	1.836	2nd vertical
4	3.007	3rd vertical
5	3.096	2nd transversal
6	4.482	4th vertical



$$N = \frac{8\pi c f M}{k}$$

N= 137 pedestrians

FORCHHEIM FOOTBRIDGE



Bridge data:

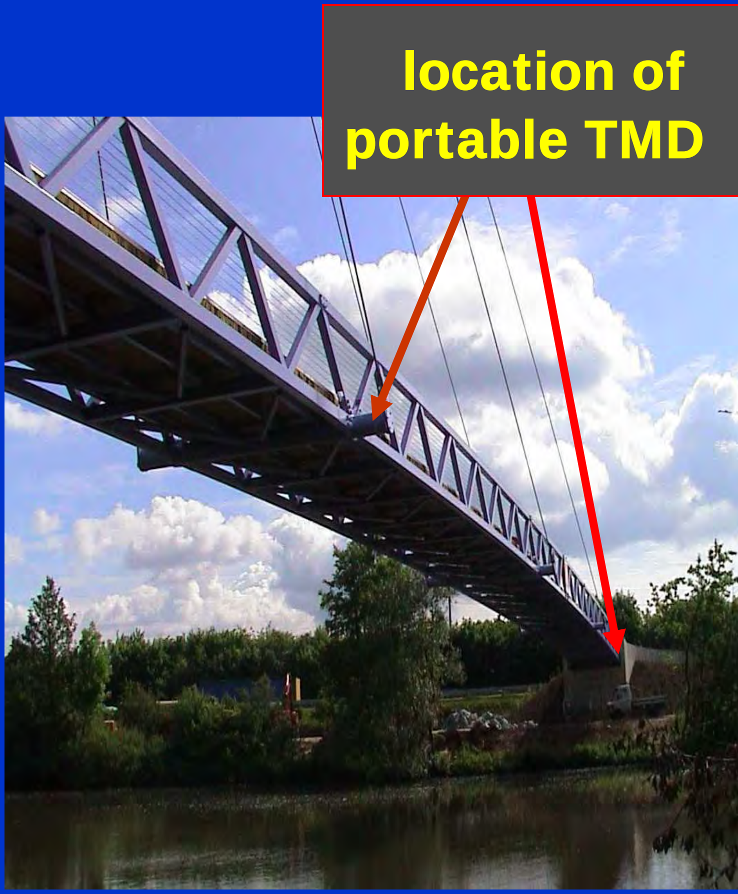
- Steel structure - 8 stay cables
- Timber footpath - Total length 117,50 m
- Deck width 4,25 m
- 1st eigenfrequencies: 1,2 - 3,5 Hz

Forchheim Footbridge

Installation of fixed TMD

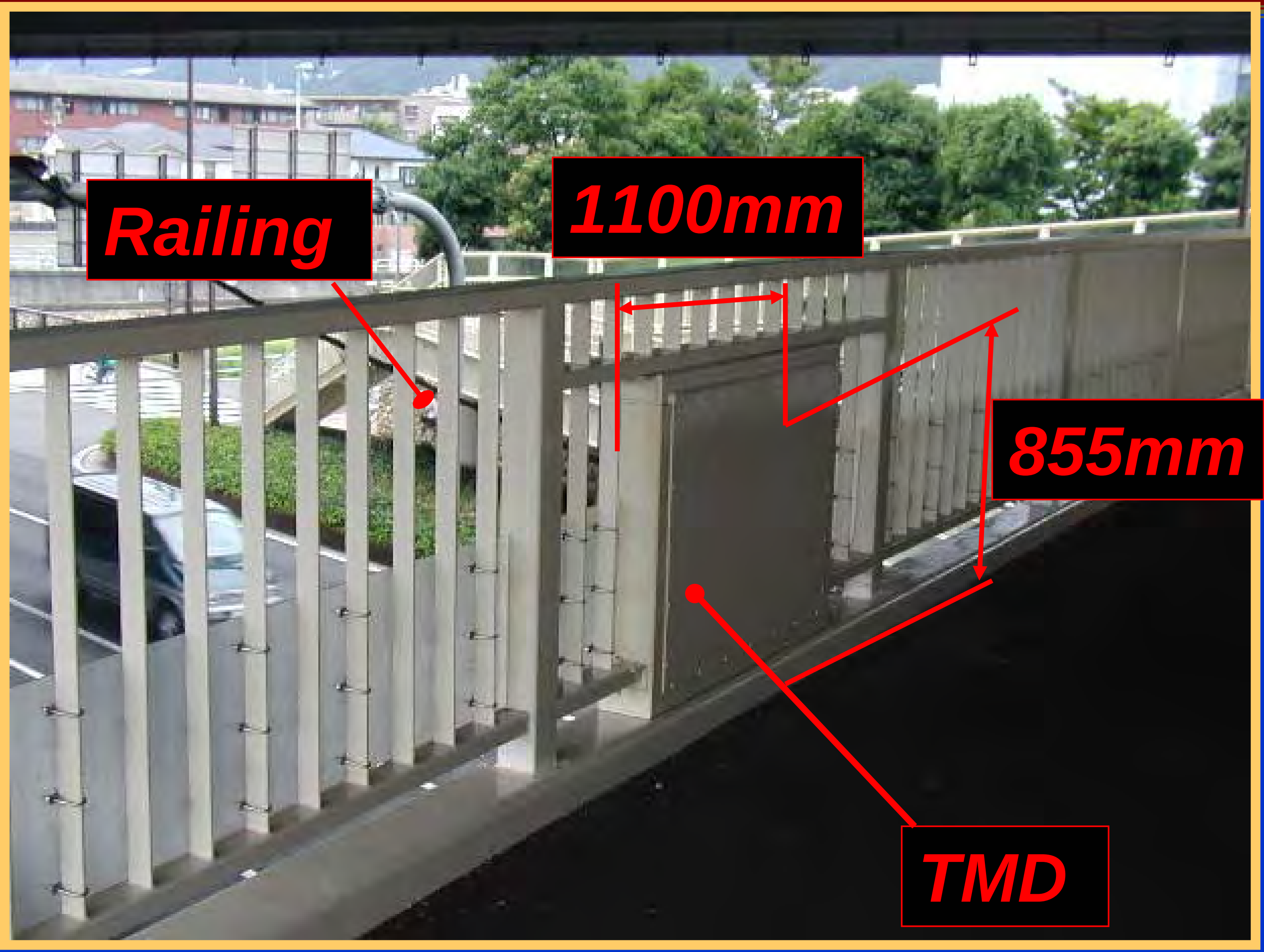
Forchheim Footbridge

Installation of portable semi-active TMD



Magnetorheological (MR) damper in fixed TMD

Setting of TMD in side railings of existing footbridges



A.HATANAKA - Japan

Deux Lions footbridge over Cher at Tours

235 m. – Vertical suspension and lateral stiffening cables

SCETAUROUTE

A .SPIELMANN

FREYSSINET

MATIERE TP

$$f = \lambda \sqrt{\frac{EI}{mL^4}}$$

WORKING GROUP AFGC-Sétra
GT 01.01

AIMS OF THE WG

- WRITING OF A SYNTHETIC DOCUMENT ON THE DYNAMICS OF FOOTBRIDGES UNDER PEDESTRIAN LOADS
- OVERVIEW OF STATE OF KNOWLEDGE
- TESTS AND RESEARCH
- DESIGN GUIDANCE
- SPECIFICATIONS

EXPERIMENTAL TESTS

- INSTRUMENTATION OF SOLFERINO FOOTBRIDGE
  - Dampers
  - Crowd loads

- LABORATORY TESTS
  - Lateral dynamic behaviour

- NUMERICAL SIMULATION
  - Lock-in effect

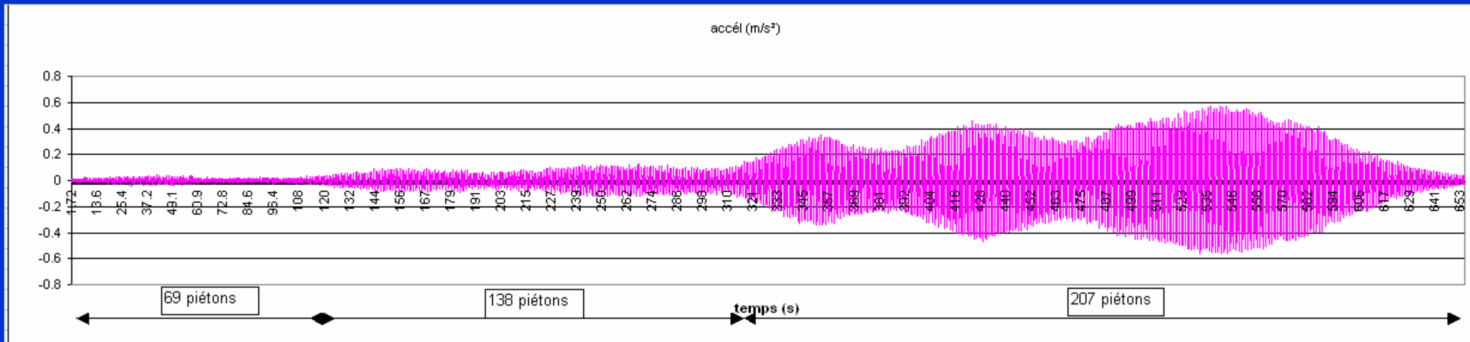
CROWD LOCK-IN EFFECT

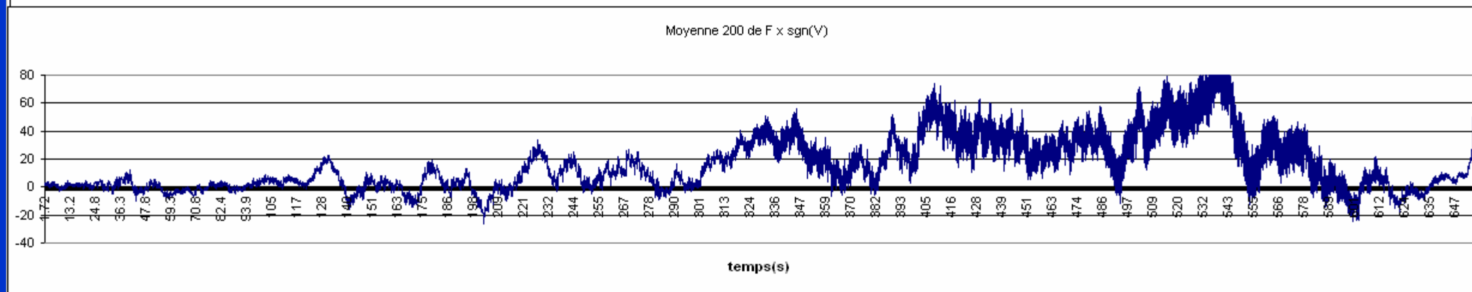
- People in a crowd walking with random frequency and phase steps gradually synchronise their motion with the deck lateral motion under certain conditions.

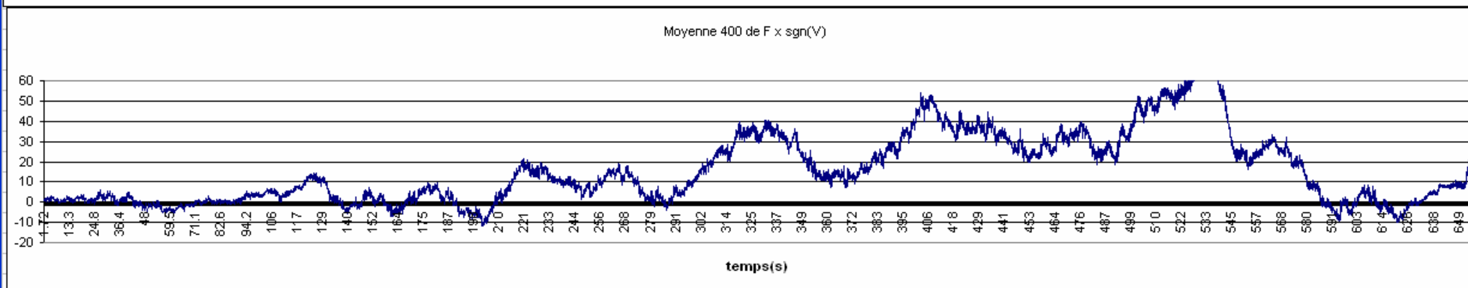
-

- Threshhold value:
  - Critical nimber of pedestrians
  - Critical acceleration
  - Self-excited lateral response of footbridges due synchronised pedestrian loading

Tests on Solférino Footbridge – Lock-in effect







Synchronisation réelle	**5.80%**	**6.52%**			**10.87%**		**16.91%**				**24.15%**			
8,6 racine(ksi n) / n	6.04%	4.27%			4.27%		3.49%				3.49%			
Fujino 0,2 n	20%	20%			20%		20%				20%			
accélération (m/s²)	0.04	0.08			0.12		0.15				0.45			

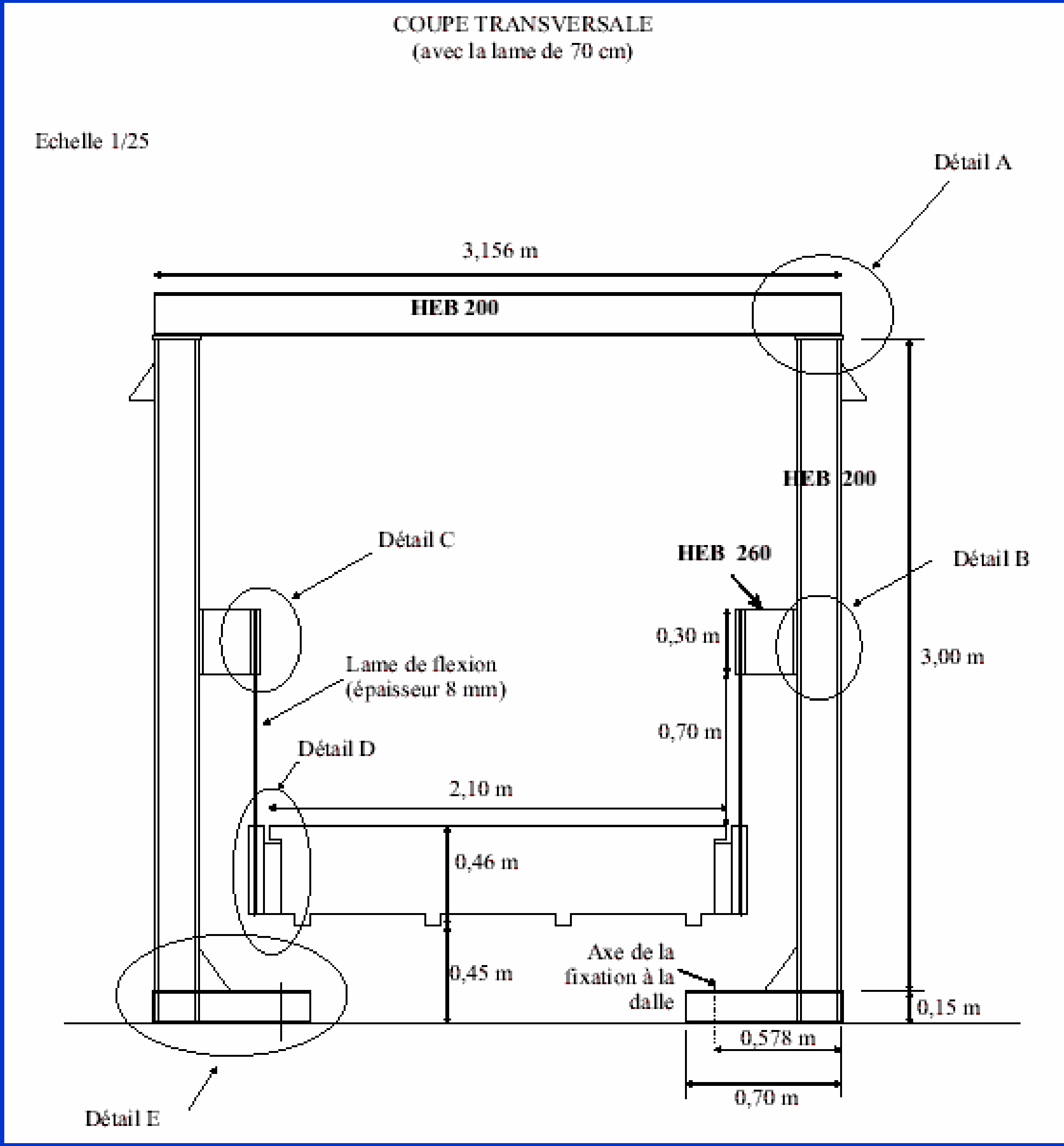
Laboratory Tests at LRPC in Paris

Laboratory Tests at LRPC in Paris

Wobbling deck model

1 DOF

fo = 0.53 Hz

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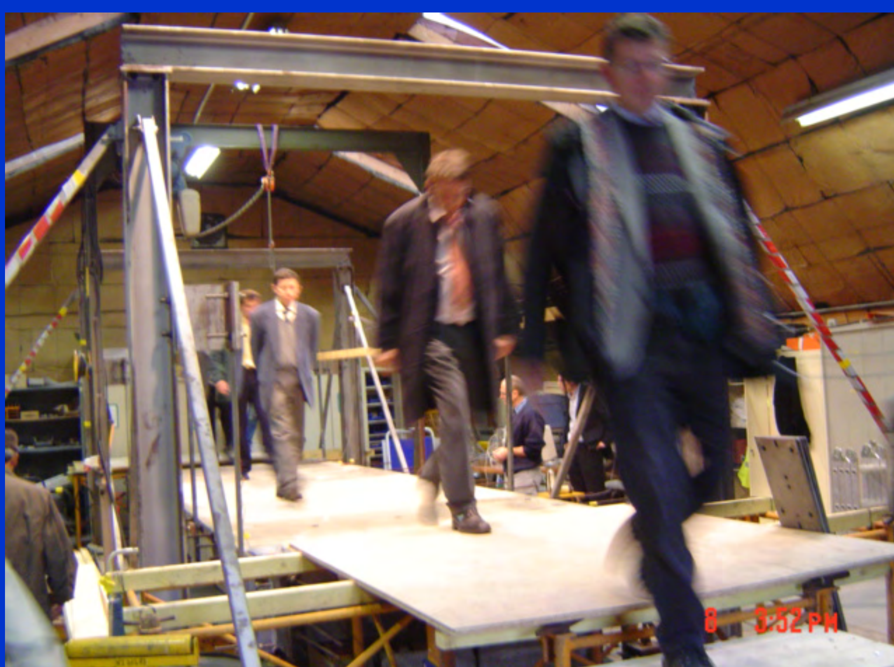
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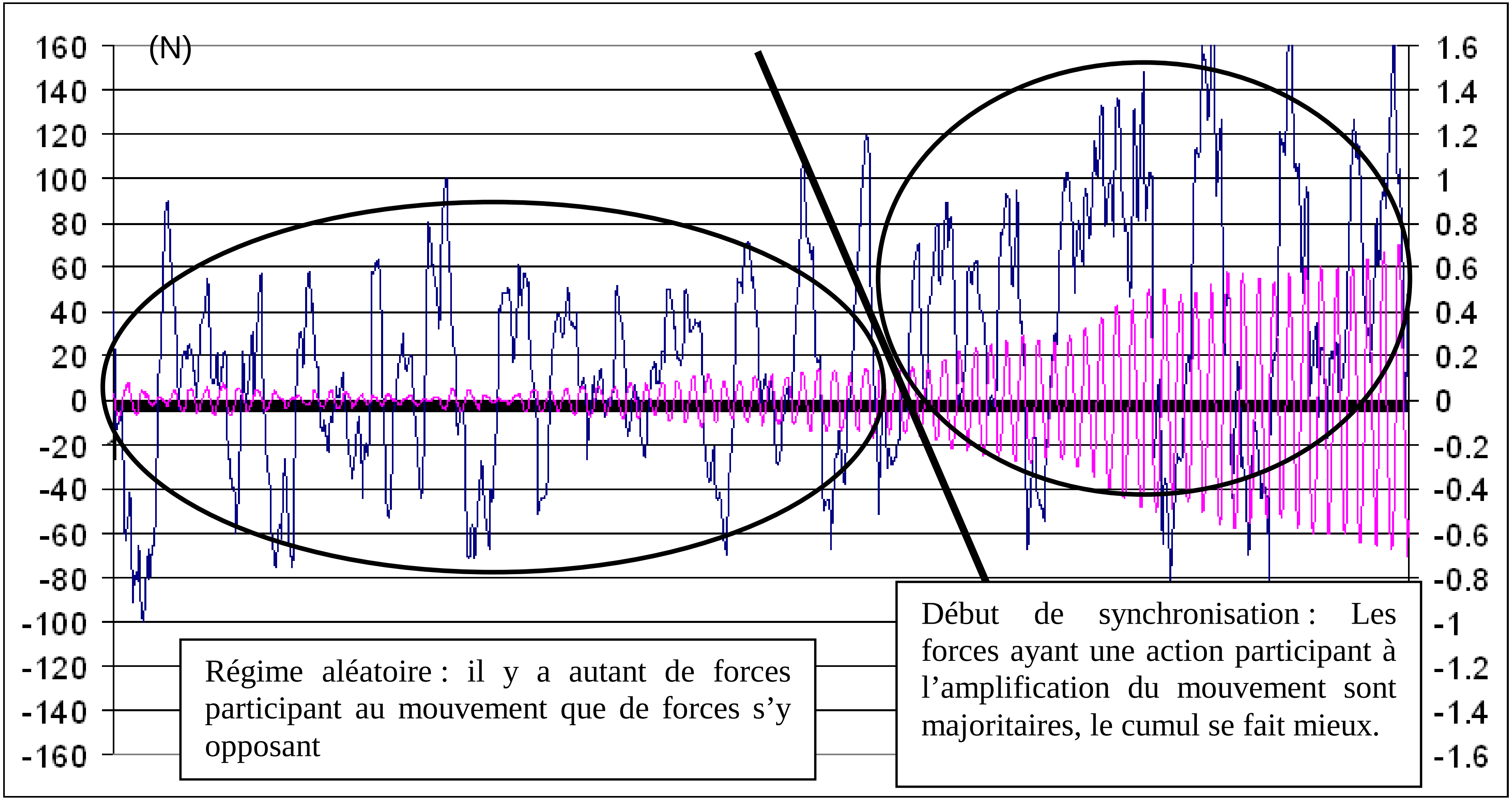
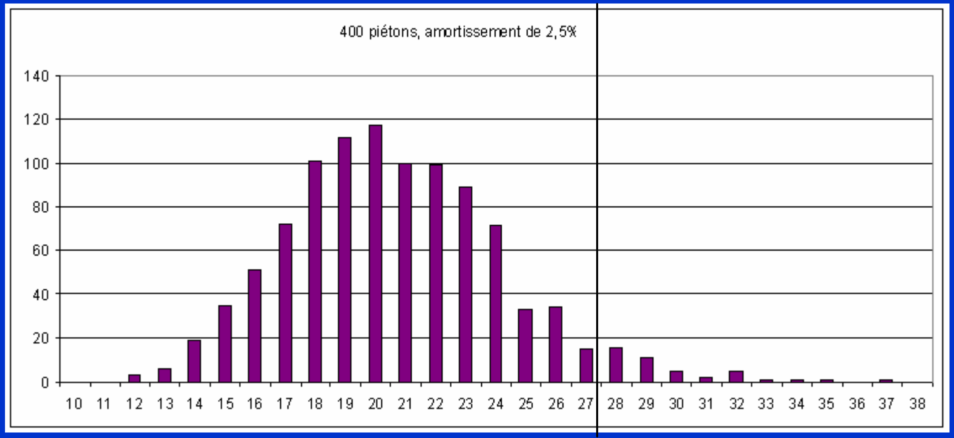
Test on platform



Above a threshold value of 0.15m/s², the pedestrian lateral force is clearly more efficient and synchronisation seems to start.

NUMERICAL SIMULATION FOR RANDOM CROWD

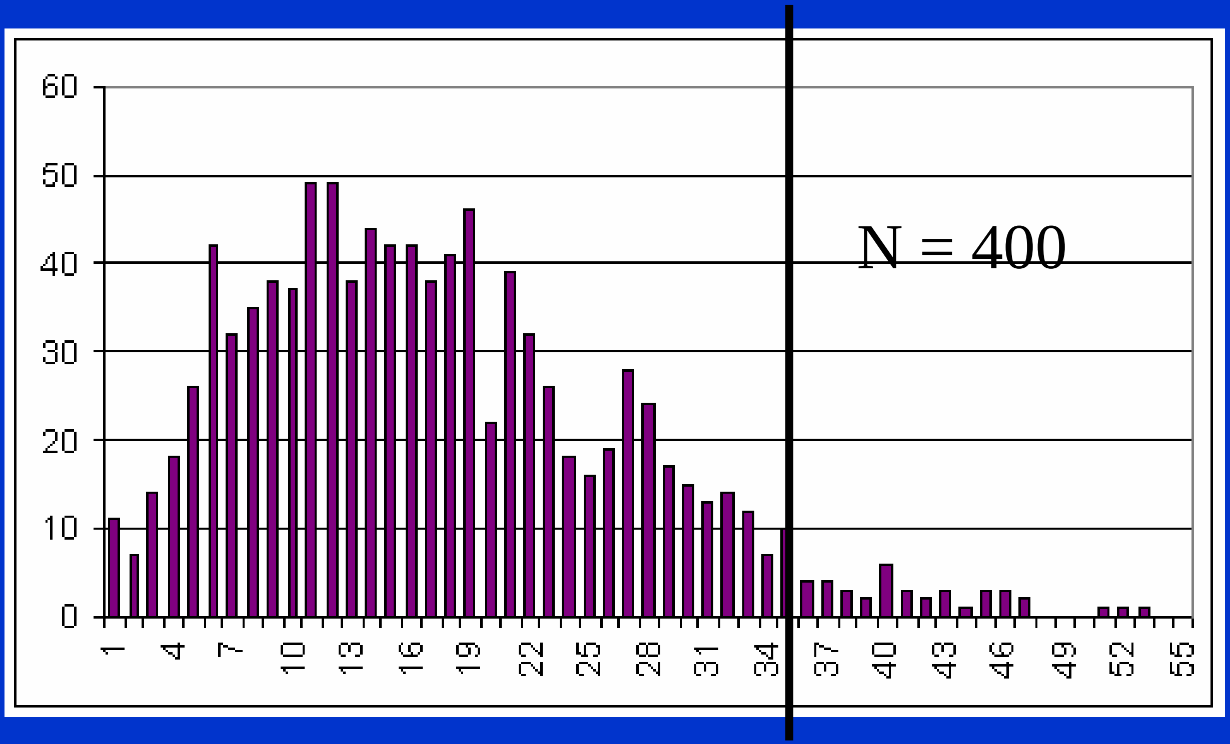
- Probabilty and statistical method :
- For each N pedestrians – a random phase and frequency in a gaussian distribution centered on the bridge frequency (2 Hz) and r.m.s of 1,75 Hz
- Different damping values ξ
- Maximum accelration and number of equivalent in phase pedestrians (95%).



$$N_{eq} = 8{,}6\sqrt{N\,\xi}$$

NUMERICAL SIMULATION FOR RANDOM CROWD

• N pedestrians – a random phase but same frequency

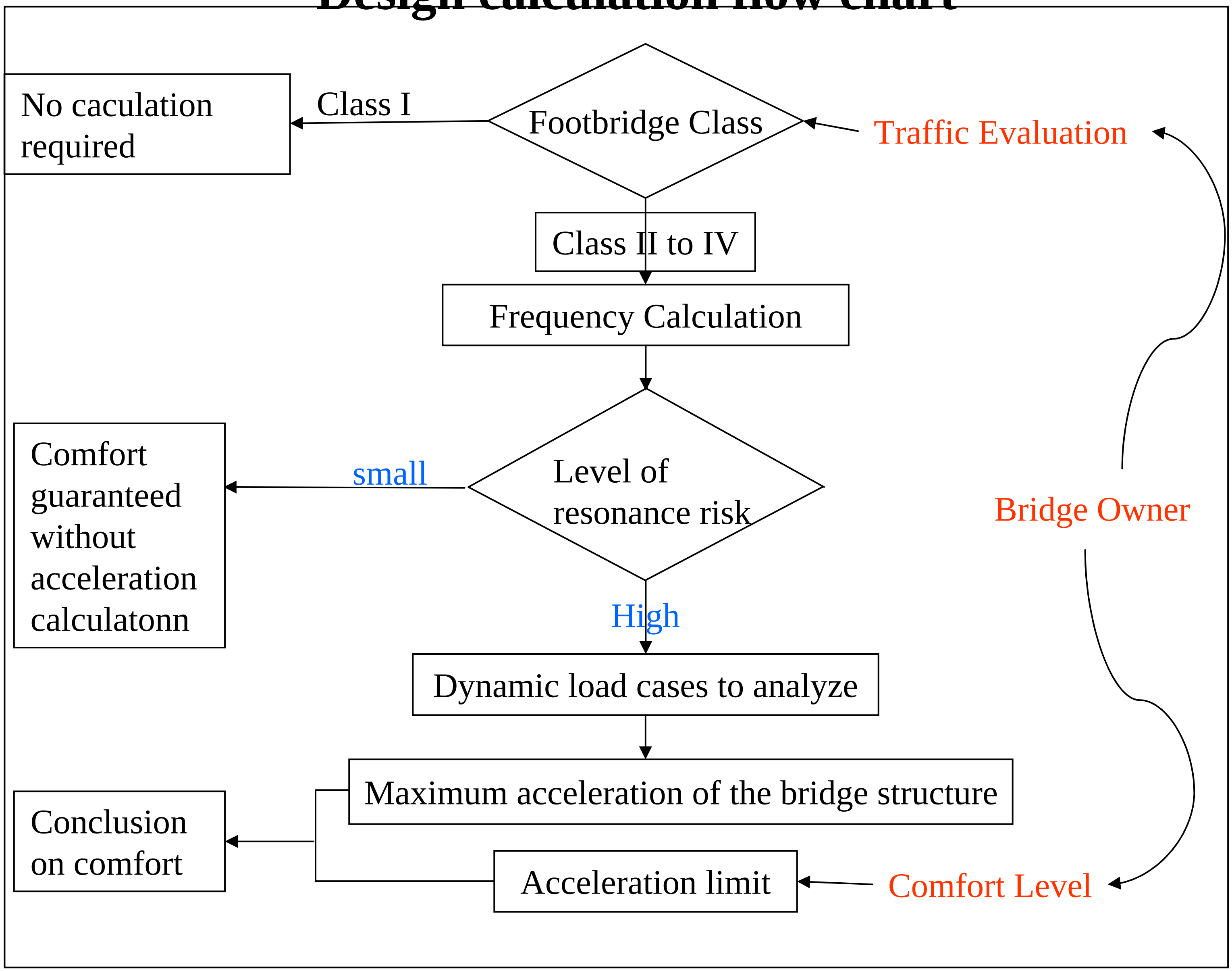


$$N_{eq} = 1,75\sqrt{N}$$

Calculation procedure for pedestrian bridges

- Choice of the footbridge class.
- Comfort level to attain.
- Calculation of frequencies and the need to calculate acceleration.
- For each mode, if the acceleration must be calculated :
  - Load cases definition : (Value, positionning, synchronisation, SLS,ULS),
  - Damping required
  - Acceleration values
  - Check with comfort value and lock-in effects
  - Structural modification or additional damping
  - Tests on built bridge

Design calculation flow chart



FOOTBRIDGE CLASS

Class I : Very few pedestrian, between small population zones , rural areas or just to re-establishment of rural roads above new motorways.

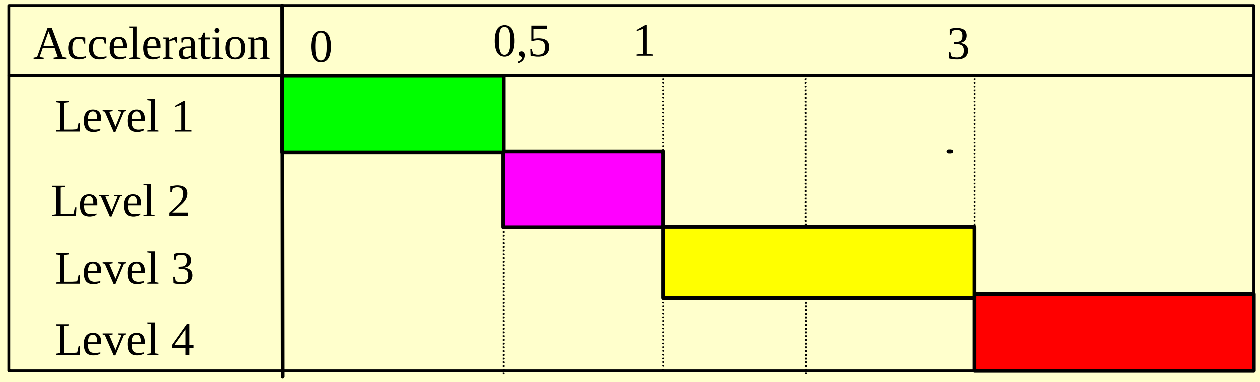
Class II : Small pedestrian traffic, with possible large groups, but no occurrence of full bridge loading.

Class III : urban bridge in densely populated zone, with frequent high traffic and possibilities of full bridge loading.

Class IV : urban bridge with dense population (near a railway or tube station, sports or concert stadium) with frequent dense crowds (festivities, tourists,) and fast traffic.

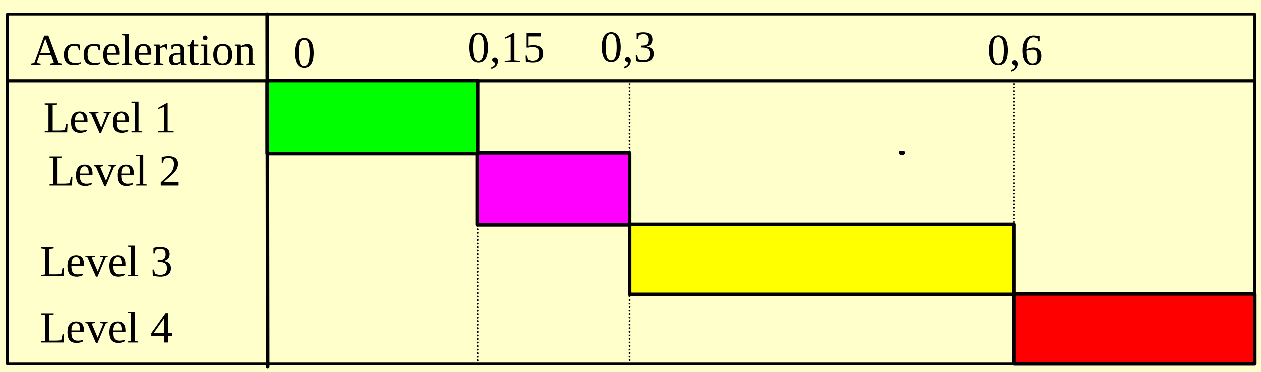
Comfort levels to be checked by bridge acceleration

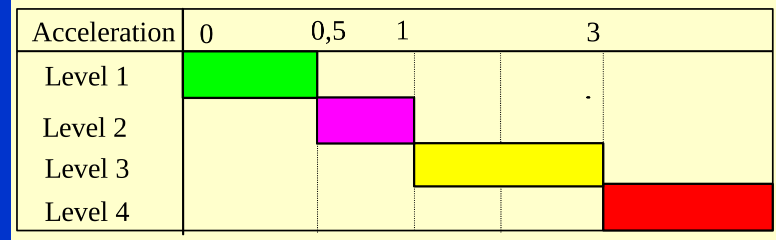
Vertical acceleration (m/s^2)



Horizontal acceleration

(m/s^2)





Comfort levels

Green : comfort « good » : If the footbridge is strategic and all discomfort to be excluded .

Pink : comfort « medium » : Most common

Yellow : comfort « poor » : If the slenderness (and flexibility) can be accepted for architectural aspect and if there will never be many pedestrians on the bridge .

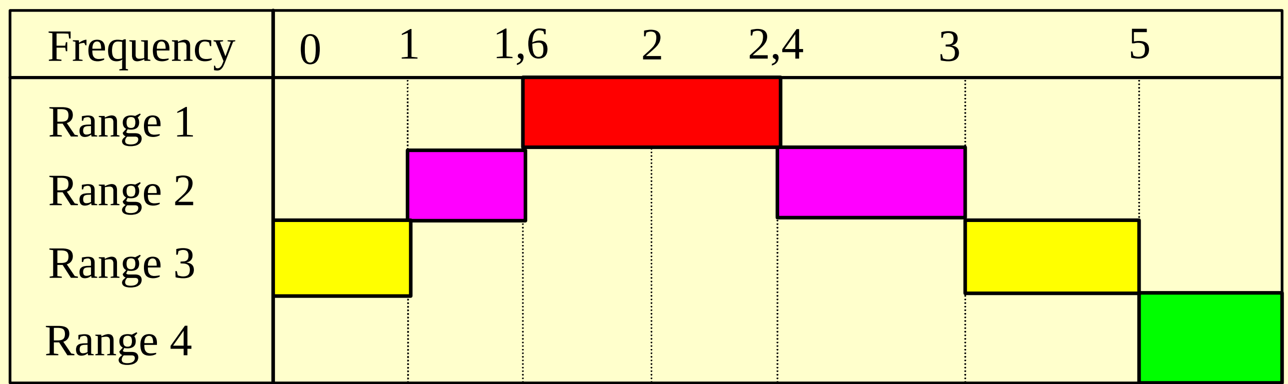
Red : very uncomfortable, to ban.

Besides comfort levels,for the lateral oscillations, a « lock-in frequency « acceleration limit of 0,15 m/s² is required. This is to prevent synchronisation of pedestrian motion with the bridge structure leading to unconfortable acceleration.

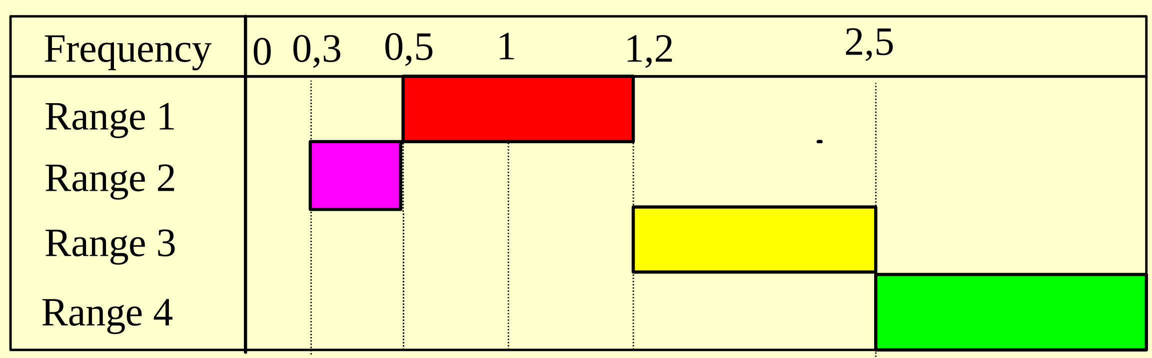
Design Calculations

Frequency calculation for class II, III and IV and choice for further calculation of bridge acceleration

Vertical Frequencies



Horizontal Frequencies



Step 2 : Need for further calculations

	Class I	Class II	Class III	Class IV
Range 1	no calculation	calculation necessary	calculation necessary	calculation necessary
Range 2	no calculation	no calculation	calculation necessary	calculation necessary
Range 3	no calculation	no calculation	no calculation	calculation necessary
Range 4	no calculation	no calculation	no calculation	no calculation

Step 3 : Evaluation of acceptable acceleration

	Classe I	Classe II	Classe III	Classe IV
Level 1		**acceptable**	**acceptable**	**acceptable**
Level 2		**acceptable**	**not acceptable**	**not acceptable**
Level 3		**not acceptable**	**not acceptable**	**not acceptable**
Level 4		**not acceptable**	**not acceptable**	**not acceptable**

Design Calculations

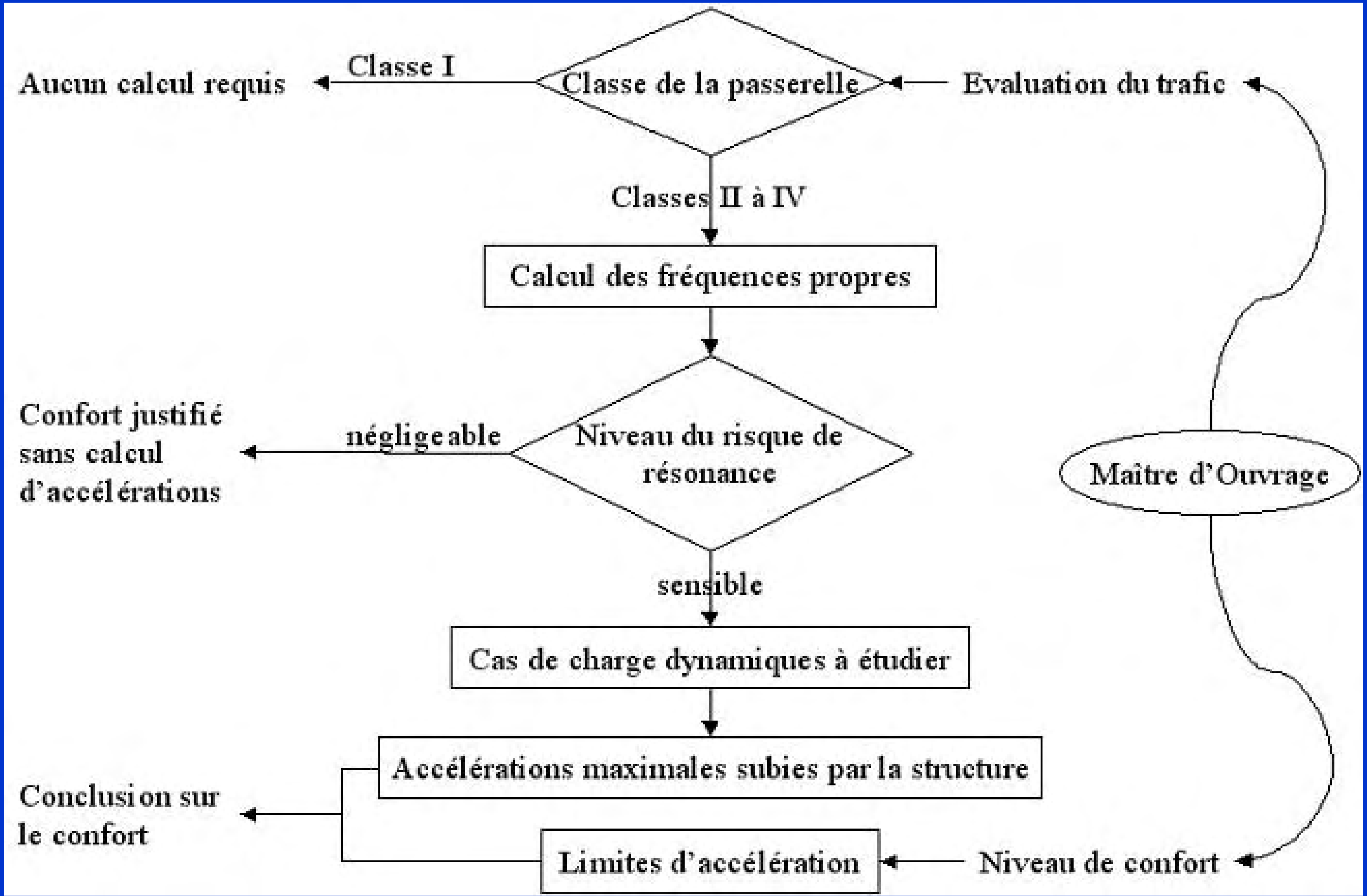
- Need for acceleration calculation

Traffic	Class	Frequency Calculation	Load case to use for acceleration check				
Low	I	NO	Frequency range of bridge				
			1	2	3	4	class
Normal	II	YES	Load case 1	none	none	none	II
Dense	III			L.c 1 and 4 3 optional	L.c.4 L.c.3 optional	none	III
Very dense	IV		Load case 2	L.c. 2 and4	L.c. 3 and 4	none	IV

case 1 : Sparse and dense crowd
case 2 : Very dense crowd

case 3 : Group of joggers
case 4 : Supplementary crowd load (2° harmonique)

Design calculation flow chart



Design calculations

Structural damping values

Deck material	***Percentage of critical damping***
Reinfored concrete	1,30%
Pre-stressed concrete	1,00%
composite steel concrete	0,60%
steel	0,40%

Composite different materials

$$\xi_{\text{équivalent mode i}} = \frac{\sum_{m\, matériau} (EI)_m \, \xi_{m,i}}{\sum_{m\, matériau} (EI)_m}$$

Design calculations

Sparse crowd , for class II et III footbridges

Direction	Dynamic Load
Vertical (v)	$d \times (280N) \times \cos(2\pi f_v t) \times 8{,}6 \times (\xi / n)^{1/2} \times \psi$
Lateral (t)	$d \times (35N) \times \cos(2\pi f_t t) \times 8{,}6 \times (\xi / n)^{1/2} \times \psi$ *
Longitudinal (l)	$d \times (140N) \times \cos(2\pi f_l t) \times 8{,}6 \times (\xi / n)^{1/2} \times \psi$

Gaussian frequency and randon phase distribution

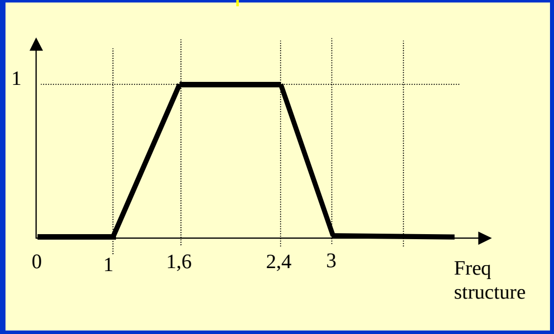
Equivalent n° $8{,}6 \times (\xi / n)^{1/2}$

(Synchronisation)

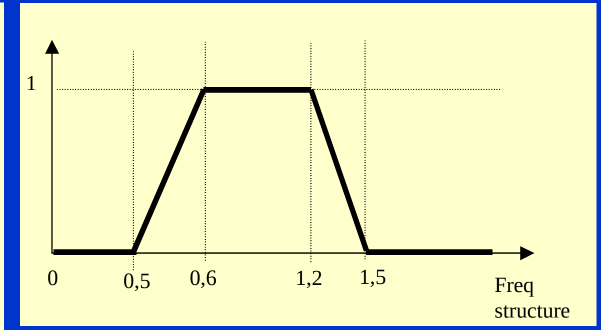
Class	Crowd density d
II	0,5 person/m^2
III	1 person /m^2

- **Acceleration below threshold value defined by the bridge owner or the lock-in lateral acceleration of 0,15m/s².**
- **If lock-in : 30% synchronisatior**

Coefficient ψ



Vertical anv longitudinal



Lateral

The reduction coefficient ψ accounts for the decrease in probability of resonance outside the walking range frequency (vertically and horizontally)

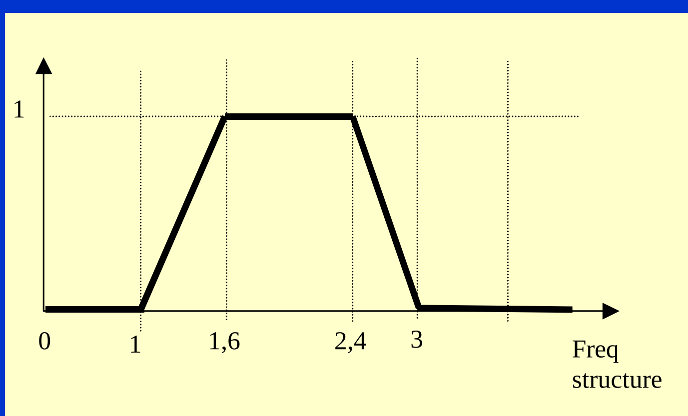
Design calculations

Dense crowd : class IV bridges only : 1,5 person/ m²

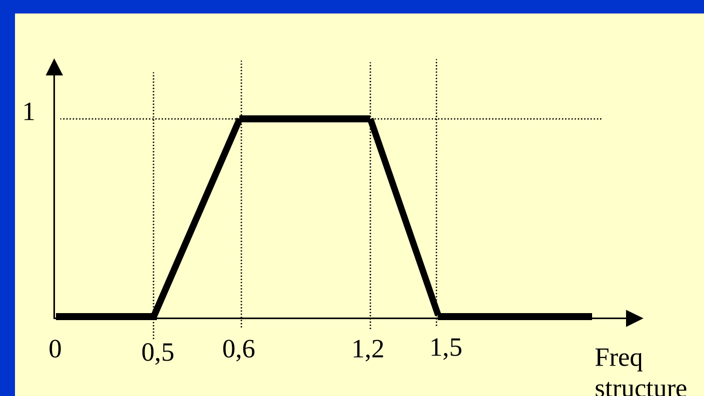
Direction	Dynamic load / m^2
Vertical (v)	$1{,}5 \times (140N) \times \cos(2\pi f_v \tau) \times 1{,}75 \times (1/n)^{1/2} \times \psi$
Lateral (t)	$1{,}5 \times (35N) \times \cos(2\pi f_t t) \times 1{,}75 \times (1/n)^{1/2} \times \psi$
Longitudinal (l)	$1{,}5 \times (140N) \times \cos(2\pi f_l t) \times 1{,}8 \times (1/n)^{1/2} \times \psi$

All pedestraian at bridge frequency, but random phase distribution

Equivalent N° = $1{,}75\ n^{1/2}$



Vertical and longitudinal



Lateral

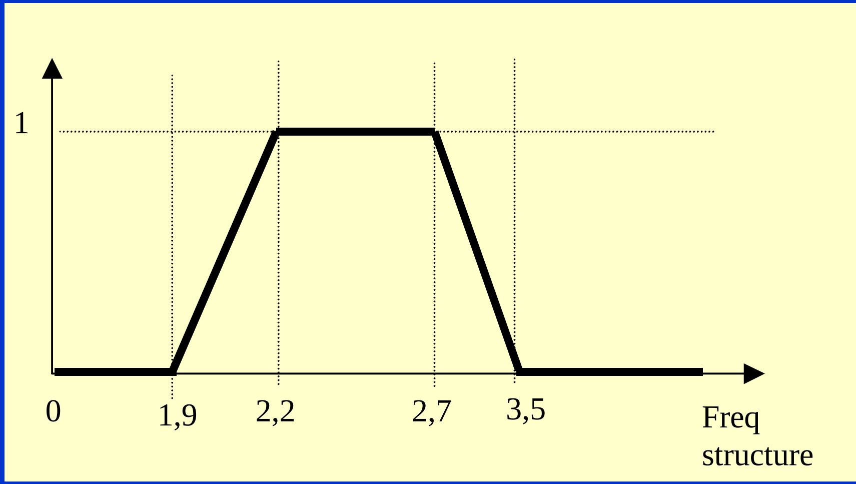
Supplementary load cases : group of joggers or walkers at second harmonics

Design calculations

Load case 3 : Group of joggers

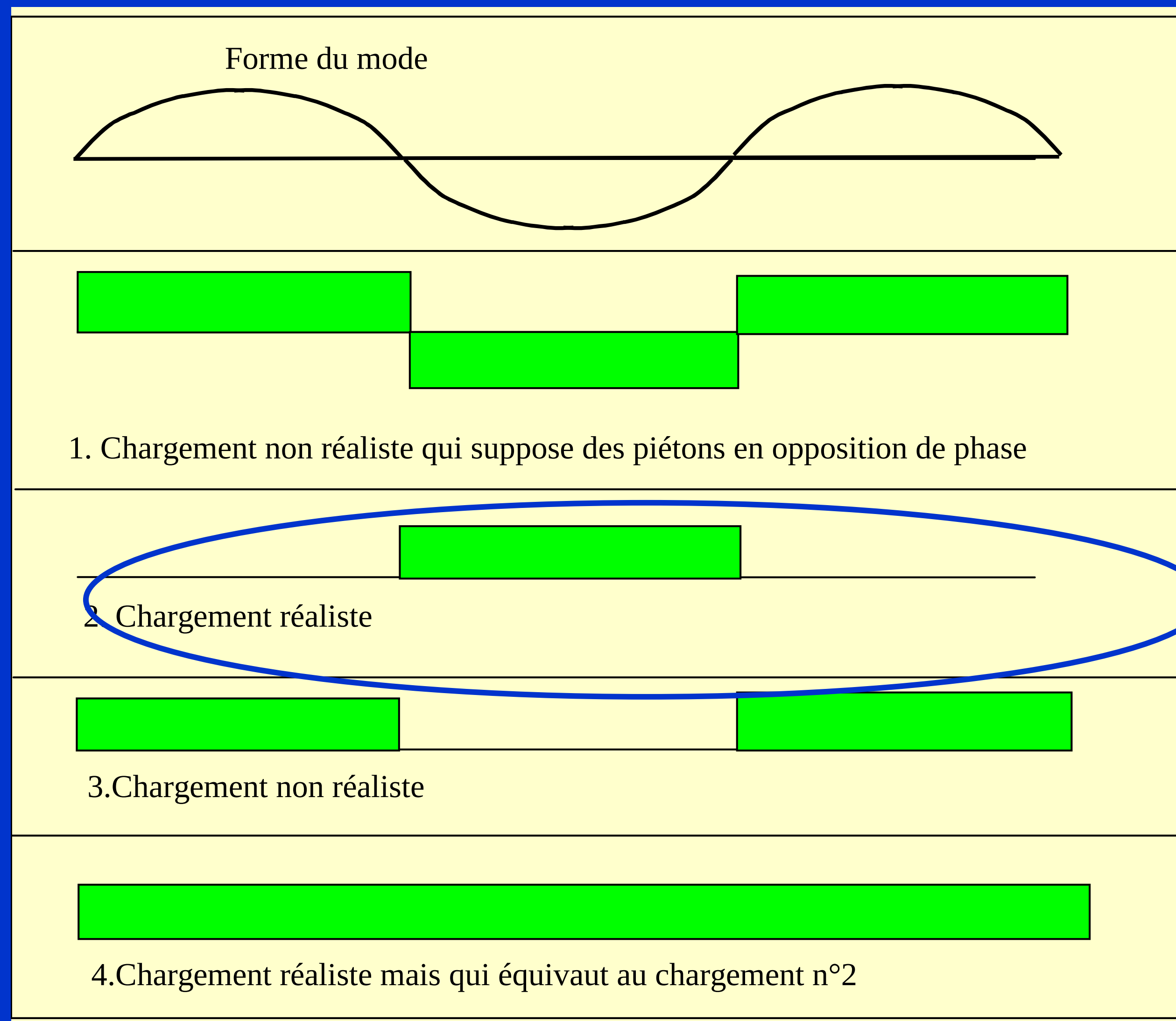
Direction	Dynamic load / m^2
Vertical (v)	$3 \times (1250N) \times \cos(2\pi f_v \tau) \times 1{,}75 \times \psi$

3 joggers at same frequency and phase at speed of 3m/s.

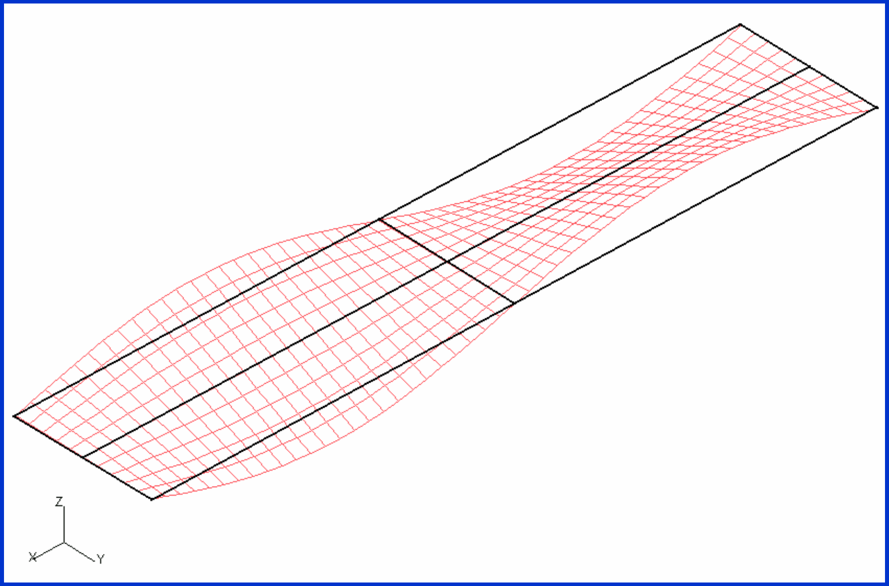


Vertical

Dynamic Load positionning (longitudinal only)



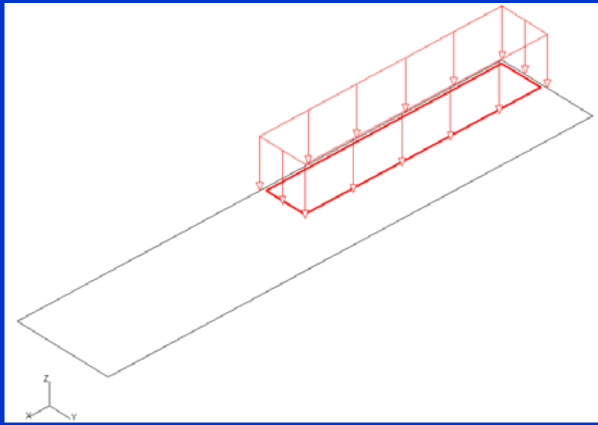
Design calculations

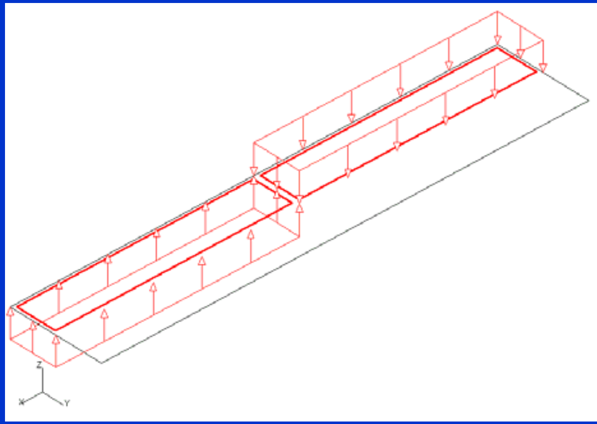


Load Positionning : longitudinal + latéral (torsional modes

Unrealistic loading: the pedestrians have to change steps at mid span !!

Realistic loading





Remedial measures against excessive acceleration

- Frequency tuning : stiffening, support conditions

- Structural modification for dynamic response : increase mass, increase the participation of non structural elements with high damping capacity : connecting the concrete deck, heavy parapets,..

- Add dampers as final solution

- Dynamic tests on built bridge to measure real damping (usually higher than the design value) and crowd tests to check the dynamic response.

SUMMARY OF REMEDIAL STEPS

Class II : The dimensionning must be slightly revised for comfort without important structural consequences

Class III : Frequency tuning is necessary to decrease the acceleration : (Stiffen the deck or add mass)

Class IV: The bridge must be highly stiffened or dampers must be added.

Design Strategies

- Frequency tuning
  - Vertical frequencies > 3Hz
  - Lateral frequencies > 1.5Hz

Not possible for long spans

- Damping
  - Tuned Mass Dampers
  - Viscous & Visco-elastic dampers

FOOTBRIDGES FOR PEOPLE

SURFACING

STONE BRICKS

SLABS

CONCRETE

EXTRUDED ALUMINIUM

RECYCLED RUBER BLOCKS

DANGEROUS SURFACING

GLASS

EXOTIC TIMBER?

DANGEROUS SURFACING

EXOTIC TIMBER?

NEW SURFACING

RECYCLED RUBBER GRANULES ON METALPROFILE

Not slippery

No inflammable

Durable

Damping

FOOTBRIDGE FOR PEDESTRIANS ??

Questions

TARGET AUDIENCE

Engineers, Architects and Designers
Teachers, Researchers and Students
Infrastructure owners
Construction Companies
Suppliers

DEADLINES

February 28, 2005: Submission of one-page abstracts in English

April 5, 2005: Notification of selected abstracts

May 2, 2005: Final Program

July 1, 2005: Final texts in English

ADDITIONAL INFORMATION

available on website www.iuav.it/footbridge2005

Conference Secretariat
DCA - University IUAV of Venice, Italy
Graziana Tomasella
e-mail: *footbridge2005@iuav.it*
Fax: *00 39 041 5223627*

One-page abstracts in English to be sent to:
footbridge2005@iuav.it

PRIZES

Special prizes will be awarded to deserving footbridge designs presented by students and young engineers (under 35).
Additional prizes open to all participants will be sponsored by *Bridge and Design Magazine*

WORKSHOP

A special pre-conference Workshop on Pedestrian Dynamics will be held on Monday, December 5th

LOCATION

Venice, Italy

Conference Venue

NH LAGUNA PALACE

LAGUNA PALACE HOTEL
viale Ancona 2
30172 Venezia Mestre, Italy
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Ethics and aesthetics in modern design trends
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Human behaviour and the urban context
Secondary elements, balaustrades, lighting and finishes

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Advanced and simplified methods of analysis
Computer modelling and analytical techniques
Static and dynamic loading and response prediction
Risk and reliability methods
Developments in codes and standards

INSTRUMENTATION, TESTING AND MONITORING

Full scale and model testing and monitoring
Intelligent systems for bridge management and maintenance
Feedback from full scale measurements to influence future design
Development in instrumentation and bridge monitoring system

DYNAMIC RESPONSE AND CONTROL

Dynamic response to wind and use of CFD and physical testing
Pedestrian excitation, response and discomfort criteria
Active, semi-active and passive response control systems
Wind flow modification and aerodynamic design

NEW MATERIALS AND CONSTRUCTION METHOD

Applications for new structural materials
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Excursion to Venice Footbridges
Interactive Presentations -Posters

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