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Autor: Allen, D.E. / Dalgliesh, W.A.

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Dynamic Wind Loads and Cladding Design

Surcharge dynamique due au vent et calcul du parement

Dynamische Windbelastung und Bemessung von Gebäudeverkleidungen

D.E. ALLEN W.A. DALGLIESH
Division of Building Research
National Research Council of Canada
Ottawa, Canada

Windstorm damage to cladding (exterior surfaces) of buildings often results in considerable economic loss and sometimes personal injury. The same care should therefore be given to cladding design and research as is given to the structure. This discussion looks at two aspects of the design of cladding to resist wind loads: (a) how behaviour under dynamic wind loads affects resistance of both metal (ductile) and glass (brittle) panels; (b) what risks of cladding failure are implicit in North American design rules. The problem of determining actual wind loads on cladding, the greatest unknown in the design problem, is not discussed.

Design of Cladding to Resist Wind Loads

Because turbulent wind is a dynamic loading, recent design approaches for structures are based on a dynamic component that takes into account wind turbulence, size of building (averaging effect on turbulence), and dynamic amplification. A similar approach is suitable for cladding design (Fig. 1)

$$\frac{R}{FS} \geq w_o = \bar{w}\, C_g = \bar{w}\,(1 + g.I_T) \qquad (1)$$

where R is the design resistance, FS the design safety factor, w_o the design wind pressure, $\bar{w}$ the mean wind pressure equal to the mean velocity pressure $\bar{q}$ times the shape factor C_p, C_g the gust factor, I_T the rms (root mean square) intensity of wind pressure turbulence and g a peak factor relating peak wind pressure to rms intensity of turbulence. For a stationary Gaussian loading, the expected peak factor $\bar{g}$ is given in Table I, based on the theory given in Ref. (1) and assuming there are 0.3 peaks per second, a figure obtained from full-scale pressure measurements[2].

When I_T is zero the loading is static and the resistance R corresponds to that for a statically loaded panel. Since the effect of dynamic loads on resistance is related only to the turbulent component of the wind, it is appropriate to consider this and other structural effects, such as dynamic amplification, by a modification of the peak factor g in Eq. (1), i.e. by multiplying g by a "gust material" factor, k_m,

$$C_g = 1 + k_m . g . I_T \qquad (2)$$

The "gust material" factor, k_m, depends both on the material and structural behaviour and on the nature of dynamic loading; it will be shown that for cladding this factor is nearly equal to 1.

The natural frequency of metal and glass panels varies from about 5 to 50 Hz. In most cases this frequency is considerably higher than significant wind turbulence frequencies.[3] Thus during elastic deformations a panel can be represented as a statically loaded structure and dynamic amplification can be neglected. Only for unusual, high-frequency wind turbulence created locally by building corners[4] or by surface irregularities, such as mullions, is dynamic magnification likely to become significant.

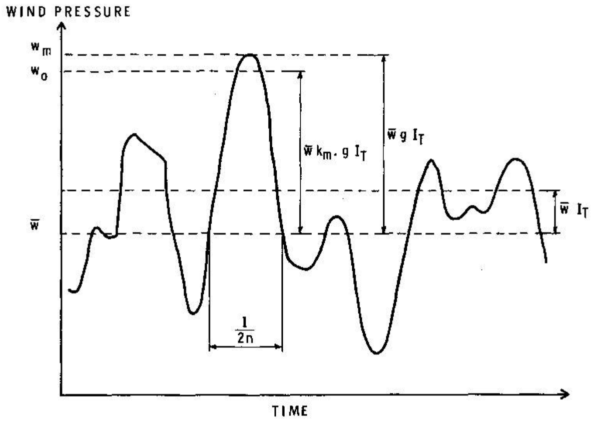

Figure 1: Wind Pressure Representation for Cladding Design

Metal Cladding

Metal panels fail by yielding, by buckling, or by fracture of the connections. Two aspects of metal behaviour are discussed in this paper: rate effect, i.e. change of yield strength with rate of loading, and the effect of plastic deformation. Metal fatigue is neglected in this study.

TABLE I - PEAK FACTOR AND GUST FACTORS FOR GLASS

Duration of Load	Expected Peak Factor for Loading $\bar{g}$	Glass (Fig. 3)	
		$k_m . g$	Minimum, C_g
one hr.	3.9	4.0	2.0
10 min.	3.4	3.2	1.7

According to information on rate effect for steel,[5] a ten fold increase in rate of loading increases the yield stress, σ_y, by approximately 2 ksi. Since the standard ASTM testing rate [6] corresponds approximately to 10 ksi per second, the rate effect can be approximated by

$$\sigma_y - \sigma_o = 2 \log \left(\frac{\dot{\sigma}}{10}\right) \qquad (3)$$

where σ_o is the yield stress according to the standard test.

Plastic deformation can also absorb an exceptional temporary overload; although the material may yield there may not be sufficient permanent deformation to require replacement of the panel. Vickery looked into this problem for a steel building structure and found that the mean wind speed necessary to produce severe damage is about 20 per cent greater than that necessary to just produce yielding.[7]

Consider a simply-supported panel, undergoing plastic bending at mid-span. The panel is subjected to a half sinusoidal cycle of wind pressure with maximum amplitude $w_m - \bar{w}$ and forcing frequency n Hz (Fig. 1). The amount of plastic deformation, δ_p, during an excursion of wind pressure beyond yield pressure w_y can be calculated numerically from the equation of motion. Rate effect is taken into account in accordance with Eq. (3) by expressing w_y in terms of w_o, corresponding to the standard test yield resistance.

The following damage criteria are assumed: permanent deflection: $\frac{\delta_p}{L} = \frac{1}{50}$, and section failure: $\frac{\delta_p}{\delta_y} = 5$, whichever occurs first. The first criterion corresponds to the need for panel replacement and the second to reaching of maximum bending resistance. In corrugated panels, local buckling occurs before very large plastic deformation.

Calculations were carried out for 3 types of cladding spanning 10 ft: (1) sheet metal (weight 1 psf, $n_o = 20$ Hz); (2) normal roof decking or wall cladding (weight 8 psf, $n_o = 10$ Hz); (3) reinforced concrete or masonry (weight 50 psf, $n_o = 20$ Hz). In the calculations it was assumed that $w_y = 50$ psf and $\bar{w}/w_y = 0.5$.

The results, given in Fig. 2 in terms of k_m, show that for wind frequencies less than about 1 Hz, very little can be gained by taking into account plastic deformation and rate effect. Recalculation for normal cladding, Case (2), assuming strain hardening factors (ratio of inelastic stiffness to elastic stiffness) of 0.01 and 0.1 indicate that strain hardening is no more significant for dynamic resistance than it is for static resistance.

Thus design wind loads for metal cladding failing primarily by yield can be determined by assuming that the panel is a static structure which fails when the wind pressure exceeds the standard plastic resistance. Some extra resistance is available for rare local high-frequency wind turbulence.

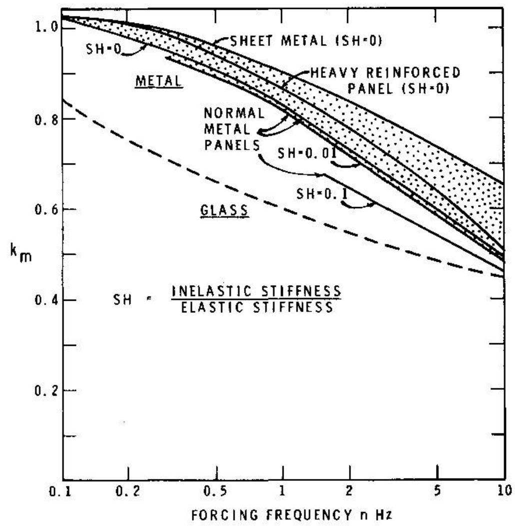

Figure 2: Gust Material Factor k_m for One Cycle of Loading

Windows

Glass is a brittle material in which failure starts at an invisible surface or edge flaw. Its strength is dependent on window size (in accordance with the theory of weakest flaws), rate (or duration) of loading, and, to a lesser extent, on temperature and relative humidity. Rate of loading, the only effect of interest to this study, can be approximated by the following criterion:[8]

$$\int_0^{t_f} w^{12}\, dt = C_M \tag{4}$$

where w is the pressure and t_f the time at failure. On the basis of manufacturers' loading tests[9] - a gradually applied pressure in which failure occurs at about one minute, the constant C_M is determined from Eq. (4) to be $4.62\, w_o^{12}$, where w_o is the failure pressure from the standard test. Based on one peak of sine wave loading (Figure 1), Fig. 2 shows that glass is considerably more sensitive to rate effect than metal, although for a load of very short duration (high n) metal gains on glass because of its ductility.

Because of this sensitivity to rate effect, one peak of loading does not provide useful information for glass. Figure 3 shows the results of applying the damage criterion to a sustained random wind pressure:

$$\int_0^T w^{12}\, dt = \bar{w}^{12} \int_0^T [1 + I_T\, x(t)]^{12}\, dt = C_M \qquad (5)$$

where x is assumed to be a stationary Gaussian random process with a mean of zero and a standard deviation of one. The damage will be different for each random process of duration T but the expected damage can be determined from Eq. (5) by expanding into powers of x and replacing $\int_0^T x^n\, dt$ by its expected value based on the normal distribution, $1.3 \ldots (n-1)T$. From Eqs. (1) and (3), w_o can be eliminated and the results can be expressed in terms of $k_m \cdot g$ or C_g.

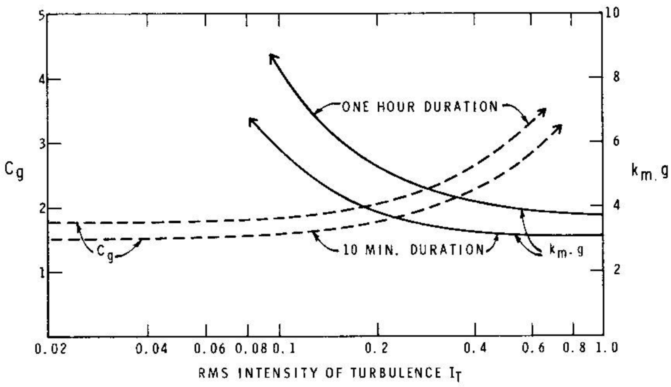

Figure 3: Gust Factors For Glass - Stationary Gaussian Loading

Figure 3 shows the results as a function of rms intensity of turbulence, I_T, for 2 load durations: 10 minutes and 1 hour. The results indicate constant values of $k_m \cdot g$ for high intensity of turbulence and constant values of C_g for low intensity of turbulence; these values are given in Table I. The former applies to most windows near the ground and the latter to windows in tall unobstructed buildings. The values of $k_m \cdot g$ compare closely to the expected peak factors $\bar{g}$, which do not consider dynamic structural effect. The results of this study therefore indicate that, except for windows subject to small turbulence, the value of k_m for glass can also be taken as 1.

Risk of Failure

The consequences of cladding failure due to wind are not as serious as for structural collapse. North American building codes allow for this, either by a one-third increase in allowable stress for metal cladding,[10] or by a reduced return period for design wind load.[11]

Annual failure risks implied by North American design rules are compared in Table II based on the following assumptions: (1) metal yield strength is distributed normally with a mean value 1.15 times the specified resistance (guaranteed minimum) and a coefficient of variation 0.10; (2) glass window strength is distributed normally with a coefficient of variation 0.25; (3) maximum annual hourly wind loads follow the extreme value Type 1 distribution with a coefficient of variation 0.30.

Annual failure risks of 0.01 to 0.3 per cent in Table II appear to be considerably higher than indicated by actual damage, probably due to conservative design assumptions. Comparative figures in Table II, however, indicate that

TABLE II - ANNUAL FAILURE RISKS FOR CLADDING

Code	Design Wind Code		Metal		Glass	
	Return Period, Years	Gust Factor, C_g	Safety Factor	Annual Failure Risk, %	Safety Factor	Annual Failure Risk, %
NBC[a] 1970	10	2.5	1.67	0.007	2.5	0.17
NBC[a] 1965	30	2.0	1.25	0.26	2.5	0.21
ANSI[b] 1972	50	2.0	1.25	0.13	2.5	0.16

a National Building Code of Canada - Sections 4.1, 4.6 and 4.7

b American National Standards A58.1 - 1972. See also Ref. (10)

recent Canadian design rules for metal cladding are too conservative; a safety factor of 1.25 would give an implied failure rate of 0.16 per cent per year. Recent window failures in tall buildings[12] indicate that falling glass from a broken window initiates failure of a number of other windows (a kind of progressive collapse). For this and psychological reasons it is recommended that design failure risks be reduced for tall buildings.

Conclusions

A study of metal for rate effect and ductility, and of glass for rate effect, shows that for turbulent wind loads, both types of cladding can be considered as statically loaded structures in which failure occurs when wind pressure exceeds the structural capacity as determined by standard tests. The factor k_m in Eq. (2), which takes into account dynamic behaviour under turbulent wind loads, can be generally taken as 1. For glass, minimum values of the gust factor, C_g, in Table I are recommended to avoid failure of windows subject to steady winds.

Annual failure risks for cladding indicate that recent Canadian rules for metal cladding are too conservative. Existing safety factors for windows in tall buildings appear to be too small.

The area of greatest uncertainty in the design of cladding to resist wind loads is in the wind loading itself, in particular the intensity of turbulence, I_T, and shape factor, C_p. This information should be obtained from full-scale measurements and boundary-layer wind-tunnel tests.

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SUMMARY

A study is made of the behaviour of ductile (metal) and brittle (glass) panels under dynamic wind loading. The results show that the effect of such factors as dynamic amplification, rate of loading and ductility can generally be neglected. Failure risks implicit in North American codes are compared; some changes in design rules are suggested, including an increase in safety factor for glass windows in tall buildings.

RESUME

On a fait une étude sur le comportement des panneaux ductiles (métal) et cassants (verre) dans des conditions de chargement dynamique dû au vent. D'après les résultats obtenus, l'effet de facteurs comme l'amplification dynamique, la vitesse de chargement et la ductilité est généralement négligeable. Les risques de rupture que sous-entendent les codes nord-américains sont mis en regard; quelques modifications dans les règles de calcul sont suggérées, y compris une augmentation du facteur de sécurité des fenêtres vitrées dans les bâtiments très élevés.

ZUSAMMENFASSUNG

Das Verhalten von zähen (Metall) und spröden (Glas) Materialien in Gebäudeverkleidungen unter dynamischer Windbelastung wird untersucht. Die Ergebnisse deuten an, dass der Effekt von Faktoren wie dynamisches Aufschaukeln, Belastungsgeschwindigkeit und Zähigkeit im allgemeinen vernachlässigt werden kann. Die in nordamerikanischen Normen enthaltenen Bruchwahrscheinlichkeiten werden verglichen. Gewisse Verbesserungen in den Berechnungsmethoden werden vorgeschlagen, u. a. eine Erhöhung des Sicherheitsfaktors für Glas in hohen Gebäuden.

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