Differential movements and stresses in high-rise masonry veneers: Case study

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This paper deals with a case study of brick masonry veneer distress on a reinforced concrete high-rise structure. The key cause of distress was the absence of a movement joint at the underside of the shelf angle at each floor level. A computer model introduced by the authors in a previous analysis paper is used to investigate the effects of various parameters on differential movements and veneer stresses. The results indicate that the provision of movement joints of at least 3–4 mm/storey would have prevented a buildup of significant veneer stress. In the absence of a movement joint, veneer stresses were found to be high enough to result in distress as observed on the case study structure. The paper concludes with a discussion of repair considerations.

Cette communication traite d'une étude de cas de défaillance d'un placage de maçonnerie lié à un bâtiment en hauteur en béton armé. La principale cause de défaillance était l'absence d'un joint de mouvement à la sous-face de l'angle en saillie à chaque niveau de plancher. Le modèle informatique que les auteurs ont décrit dans une autre communication est utilisé pour étudier les effets de divers paramètres sur les mouvements différentiels et les contraintes au niveau du placage. Les résultats indiquent que la présence de joints de mouvement d'au moins 3–4 mm par étage aurait empêché l'accumulation des contraintes au niveau du placage. En l'absence d'un joint de mouvement, on a constaté que les contraintes étaient suffisamment élevées pour entraîner une défaillance comme nous avons pu le remarquer dans notre étude de cas. La communication se termine par une discussion sur les techniques de réparation.

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1. Introduction

The first paper by the authors in this journal issue entitled "Differential movements and stresses in high-rise masonry veneers: Analysis" presented an overview of the differential movement problem between masonry veneer and structure. The movement relationships and computer model described in that paper will now be applied to a case study of an 18-storey reinforced concrete apartment building that exhibited major veneer distress. The case study will give the designer an indication of, firstly, the magnitude of movements to be expected and, secondly, the resultant stresses when proper movement joints are omitted. In order to provide the reader with a broader overview of the effects various parameters have on the differential movement issue, the basic case study is enlarged to demonstrate the effects of stress concentrations, movement joint width, insulation location, shelf angle stiffness, construction timing, and structure type. Finally, the paper discusses a number of repair options for veneers exhibiting various degrees of distress.

2. The structure

Construction of an 18-storey reinforced concrete flat plate and column apartment building was started in the summer of 1972. The building was clad with 92 mm thick clay brick masonry veneer panels, which were supported at each level on steel shelf angles and which ran in continuous vertical strips from the ground floor to the roof. The veneer was tied to a 140 mm concrete block masonry backup; 25 mm of rigid insulation and 12 mm of drywall placed on the interior face completed the wall assembly. A portion of the typical floor plan is shown in Fig. 1.

NOTE: Written discussion of this paper is welcomed and will be received by the Editor until March 31, 1987 (address inside front cover).

The shelf angle detail used on the structure is shown in Fig. 2. The shelf angle connection to the structure was made by means of a rigid strap cast-in-place at the time of the slab pour. No movement joint was provided at the shelf angle detail. This meant the brick masonry was built tight to the underside of the angle and mortar was placed at the angle's toe. Such a detail was common in the early 1970's. Note that the concrete block masonry was also built tight to the underside of the slab and hence no differential movement capability whatever was built into the structure.

Distress of the veneer was first noticed during a hot summer period when the building was only about 2 years old. Typical distress consisted of spalling of brick units at the shelf angle locations and vertical corner cracking. In general the distress was concentrated in the lower levels. The presence of iron oxide stains indicated that some corrosion of the shelf angles was occurring. In the computer analysis, the increase in the effective shelf angle thickness due to corrosion was assumed to be 0.6 mm/decade.

In the analysis of the distress by means of the computer model, a representative exterior column and its tributary area, as shown in Fig. 1, were considered. Table 1 lists some of the more important building particulars required by the program — a full list is given by Fenton (1984). A number of material and environmental details were unavailable and had to be assumed. In general the unknown parameters were assigned values that were believed to be typical. Table 2 shows the assumed deformational properties of each of the structural materials.

The building was modelled under two overall conditions:
(1) Moderate conditions: all building parameters assume typical values.
(2) Severe conditions: ambient temperatures, ultimate moisture strains, and brick veneer radiation absorptivity and freezing expansion strain assume relatively severe values.
Table 3 lists these parameters and their values for each condition.

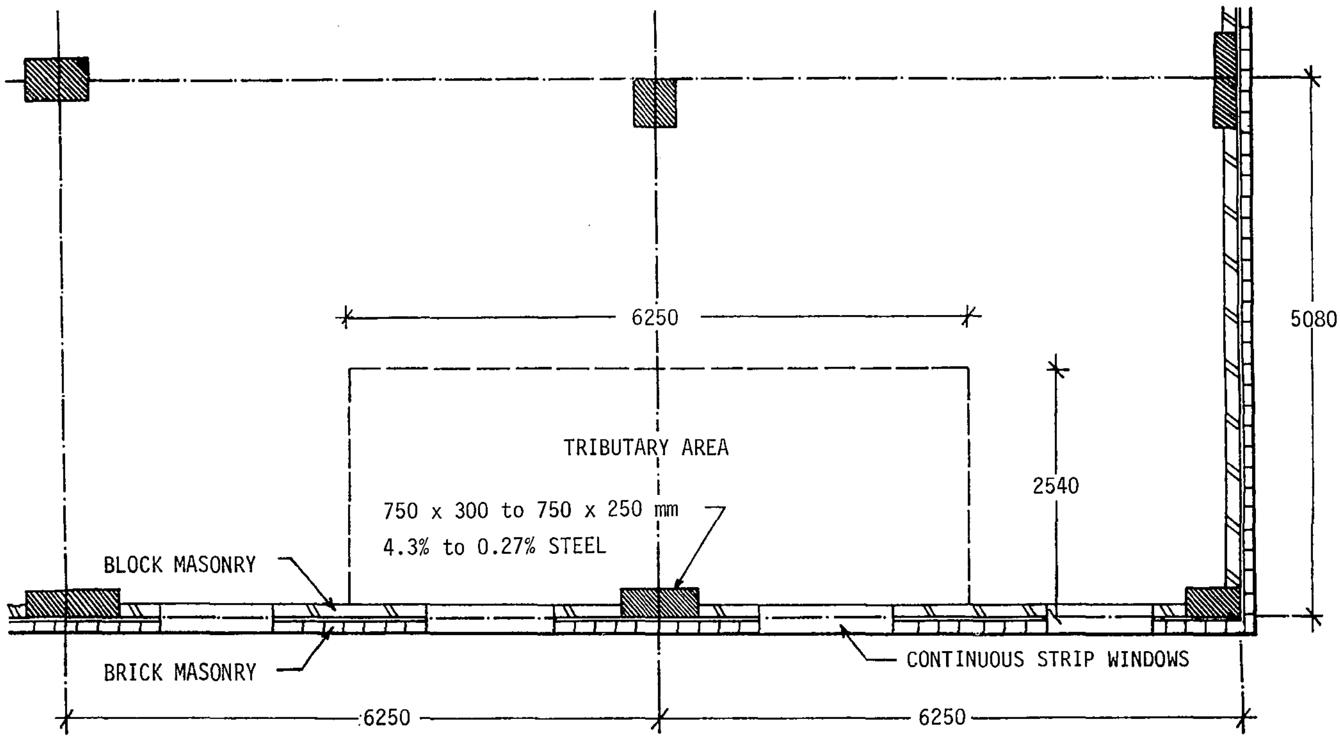

FIG. 1. Typical floor plan showing column tributary area.

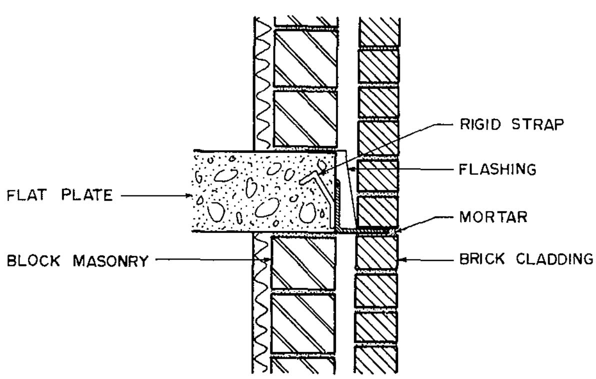

FIG. 2. Typical shelf angle connection on case study structure.

3. Results and discussion

The predicted differential movements and resulting stresses were calculated at five different times after completion of the building. The first four times of interest were during the summer (July 1) at 1, 3, 5, and 10 years of building age. The final time of interest was after 10 years during the winter. As would be expected, the maximum veneer stresses were predicted to occur at the ground level and so this paper concentrates primarily on these stresses. The variation in veneer stress with building height is discussed in Section 4.4.

Veneer, concrete block masonry, and concrete stresses have been plotted against time in Fig. 3 for moderate conditions and in Fig. 4 for severe conditions. From these plots some immediate observations can be made:

(1) Within 1 year, compressive stresses in the veneer are seen to be already 60−65% of their 10-year values.

(2) Expansion of the veneer combined with contraction of the structure and concrete masonry soon results in the slab lifting off the concrete block masonry, reducing its stress to zero within 3 years.

(3) As the compressive stress in the veneer increases, the column concrete stress reduces, becoming tensile very rapidly.

A distinction is made here between column concrete and column reinforcement. An inspection of the numerical values shown in Table 4 shows that while the concrete stresses become tensile after 1.5 years under moderate conditions and after about 6 months under severe conditions, the reinforcement stresses remain compressive and even show a slight increase with time. This is due to a transfer of load to the steel as the enclosing concrete shrinks, assuming that no slip occurs between the steel and concrete. Note that all material, except the shelf angles, are assumed to be linearly elastic in both tension and compression. If proper soft joints had been provided under the shelf angles, the concrete and reinforcement stresses after 10 years would be predicted to be −4.7 and −141 MPa respectively, which is more in line with what would be expected in design.

For a movement joint width of zero, the brick veneer restrains the downward movement of the upper slab, which, combined with column shortening, tends to put the concrete into tension. The largest concrete tensile stress of 7.6 MPa was predicted under severe conditions. Since the tensile strength of the concrete is not likely to be more than about 3 or 4 MPa, the concrete will probably crack. Once a crack occurs, a significant portion of the compressive stress in the veneer will be relieved. The assumption that the concrete remains linearly elastic under tension thus appears questionable, but the results nevertheless give a useful indication of the extreme stresses possible.

The axial compressive stresses in the brick veneer under moderate conditions are predicted to be about 6 MPa after 1 year and almost 10 MPa after 10 years. Under severe conditions, the corresponding stresses are increased to 8.1 and 12.8 MPa. The Canadian working stress masonry code CAN-S304-M84 (CSA 1984) predicts the ultimate compressive strength of this masonry to be about 20 MPa and gives an allowable axial compressive stress of 5 MPa. As the analysis is

TABLE 1. Structural and environmental parameters used in the program

Parameter	Assumed value	Comment
Storey height	2.64 m	
Tributary area	15.87 m^2	
Dead load on each level	5.51 kPa	
Live load on each level	1.92 kPa	
Orientation of wall considered	South	Azimuth = 180°
Interior air temperature	20°C	Air-conditioned all year
Average annual air temperature	6°C	
Annual ambient temperature range	36 or 42°C	See Table 3
Maximum summer afternoon air temperature	30 or 35°C	See Table 3
Minimum winter air temperature	−20 or −30°C	See Table 3
Average wind speed	1.0 m/s	Constant
Mean annual relative humidity	75%	Constant
Ground reflectance coefficient	0.20	For all levels above ground
Movement joint width	0 mm	
Shelf angle shear stiffness	300 kN/(mm·m)	
Shelf angle yield point	100 kN/m	
Date construction started	July 1, 1972	
Date construction completed	Feb. 18, 1973	
Time required to complete each level	10 days	
Level that frame construction had started when block first placed	5	Block work started in basement
Level that frame construction had started when brick first placed	6	Veneer started at ground level
Time lag between veneer and shelf angle placement	0 days	
Kiln-to-wall time lag for brick	30 days	
Factory-to-wall time lag for block	60 days	
Time lag between column placement and shoring removal	30 days	

TABLE 2. Assumed deformational properties

Material	Coefficient of thermal expansion (μm/(m·°C))	Ultimate moisture strain (mm/m)	Modulus of elasticity (MPa)
Concrete	9.5	−0.4 to −0.8	36 900
Steel	12.1	—	200 000
Brick unit	5.5	0.3 to 0.4	—
Mortar	9.0	−0.36	—
Brick masonry	7.1	—	17 900
Block masonry	9.2	−0.4 to −0.6	10 400

NOTE: Where ranges are indicated, refer to Table 3.

TABLE 3. Parameters varied under moderate and severe conditions

Parameter	Condition	
	Moderate	Severe
Minimum winter temperature	−20°C	−30°C
Summer afternoon temperature	30°C	35°C
Annual temperature range	36°C	42°C
Ultimate concrete shrinkage	−0.40 mm/m	−0.80 mm/m
Brick solar absorptivity	0.80	0.90
Ultimate brick moisture expansion	0.30 mm/m	0.40 mm/m
Brick freezing expansion	0.0 mm/m	0.1 mm/m
Ultimate block shrinkage	−0.40 mm/m	−0.60 mm/m

carried out under service load conditions, it appears appropriate to compare the predicted veneer stresses with the allowable; in all cases beyond 1 year, they are seen to be greater. Although this indicates an increased probability of failure, the predicted stresses still fall short of the expected ultimate masonry compressive strength of 20 MPa. As will be discussed in the following section, other workmanship and geometry effects can lead to significant stress concentrations, which in turn can lead to failure as observed on the structure.

The stresses predicted in each of the elements are shown to be reduced in magnitude during the winter (Table 4). This is due primarily to thermal contraction of the brick veneer. Thus it appears likely that if veneer distress is going to occur on a building with an enclosed or protected structure it will probably occur during the summer—particularly if the veneer was placed during the winter. This agrees with observations made on the case study structure.

The unrestrained vertical movements of each of the ground floor elements are summarized in Tables 5 and 6. These movements are predicted from the time of placement of each element and so are not strictly comparable. For instance, Table 5 seems to indicate that the total differential movement between the veneer and column is (1.25 + 1.91) or 3.16 mm. However, the

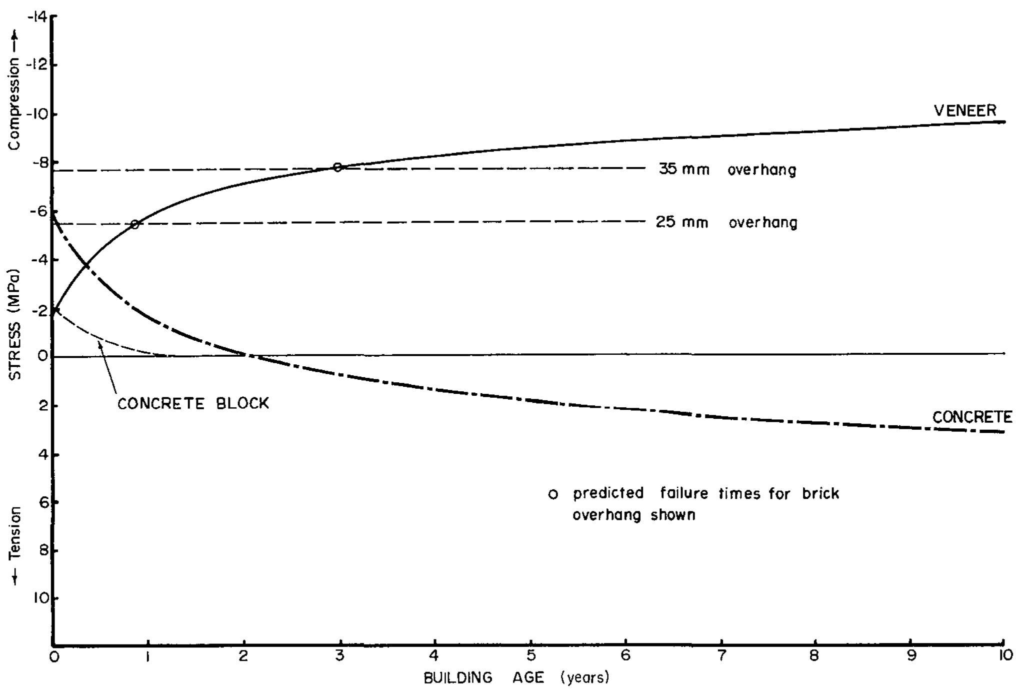

FIG. 3. Ground level veneer, concrete block, and concrete stresses under moderate conditions.

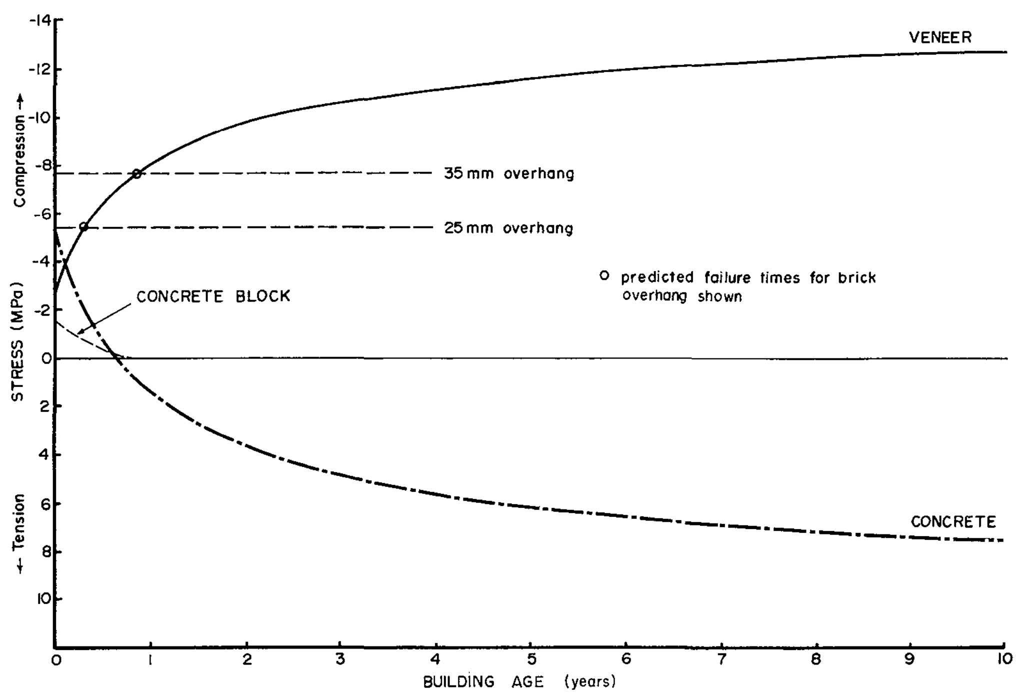

FIG. 4. Ground level veneer, concrete block, and concrete stresses under severe conditions.

column had already contracted by 0.36 mm (0.48 mm under severe conditions) by the time the brick and block masonry was placed. Thus the actual differential movement, as seen by the veneer, would be (3.16 − 0.36) or 2.80 mm.

Tables 5 and 6 also seem to indicate that thermal movements play a minor role in the veneer–structure interaction. It should be pointed out that the thermal strains of both the veneer and structure at ground level would increase significantly if the ground level had been constructed during the winter. Under the given conditions, though, the major factors are creep and shrinkage of the structure, making up about 60% of the total differential movement.

4. Other effects

The uniform axial stresses predicted in the veneer of the case study building, although usually greater than allowed by the CAN-S304-M84 masonry code, were also seen to be significantly less than the expected ultimate compressive strength of the masonry. To account for the degree of distress observed on the structure it is believed that a number of other factors, acting

TABLE 4. Predicted case study ground level stresses

Condition	Building age (years)	Season	Stress (MPa) Veneer	Block	Concrete	Reinforcement
Moderate	1	Summer	−5.88	−0.14	−1.55	−61.2
	3	Summer	−7.68	0	0.82	−69.5
	5	Summer	−8.49	0	1.83	−70.2
	10	Summer	−9.52	0	3.02	−68.3
	10	Winter	−8.37	0	1.35	−61.0
Severe	1	Summer	−8.13	0	1.42	−70.7
	3	Summer	−10.50	0	4.80	−84.1
	5	Summer	−11.55	0	6.15	−86.1
	10	Summer	−12.78	0	7.60	−84.4
	10	Winter	−11.38	0	5.56	−75.3

TABLE 5. Unrestrained movements at ground level under moderate conditions after 10 years

Material	Movement (mm) Veneer	Block	Concrete	Reinforcement
Elastic	0	−0.28	−0.32	−1.86
Thermal	0.33	0.04	−0.04	−0.05
Moisture	0.37	−0.77	−0.82	—
Creep	0	−0.53	−0.73	—
Corrosion	0.55	—	—	—
Freezing	0	—	—	—
Total	1.25	−1.54	−1.91	−1.91

TABLE 6. Unrestrained movements at ground level under severe conditions after 10 years

Material	Movement (mm) Veneer	Block	Concrete	Reinforcement
Elastic	0	−0.35	−0.21	−2.42
Thermal	0.36	0.00	−0.10	−0.13
Moisture	0.54	−1.13	−1.64	0
Creep	0	0.59	−0.60	0
Corrosion	0.55	0	0	0
Freezing	0.26	0	0	0
Total	1.71	−2.07	−2.55	−2.55

in combination with the axial loads, should be considered as discussed by Plewes (1970, 1977) and Suter and Hall (1976). These factors can be grouped into two main categories: (1) those leading to stress concentration or instability and (2) those influencing the magnitude of the axial load transferred to the veneer. The second category consists primarily of general design considerations, such as insulation location and movement joint widths; these will be discussed later in this section.

4.1 Stress concentrations

Factors leading to stress concentrations or instability are primarily construction and tolerance issues, such as:
—placing the shelf angle directly on the brick,
—placing mortar in the joint at the toe of the shelf angle,
—improper installation or absence of masonry ties,
—variation in brick overhang beyond the toe shelf angle.

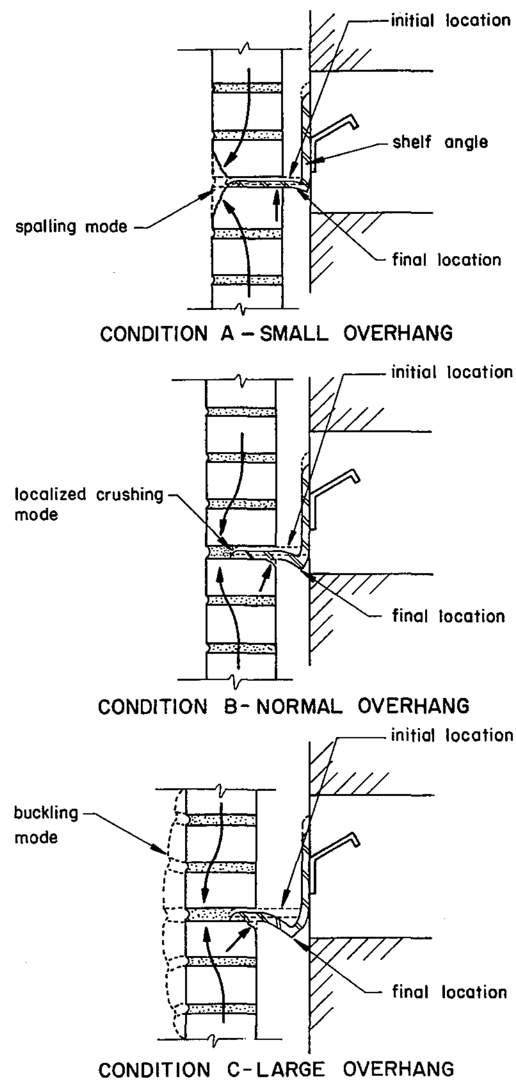

FIG. 5. Veneer failure conditions (shelf angle deformations exaggerated).

When the shelf angle is placed directly on the underlying brick surface, irregularities in that surface result in nonuniform contact and local stress concentrations. Consequently, some local crushing and spalling of the masonry can occur.

Suter and Hall (1976) postulate that the practice of placing mortar in the joint at the shelf angle toe along with variations

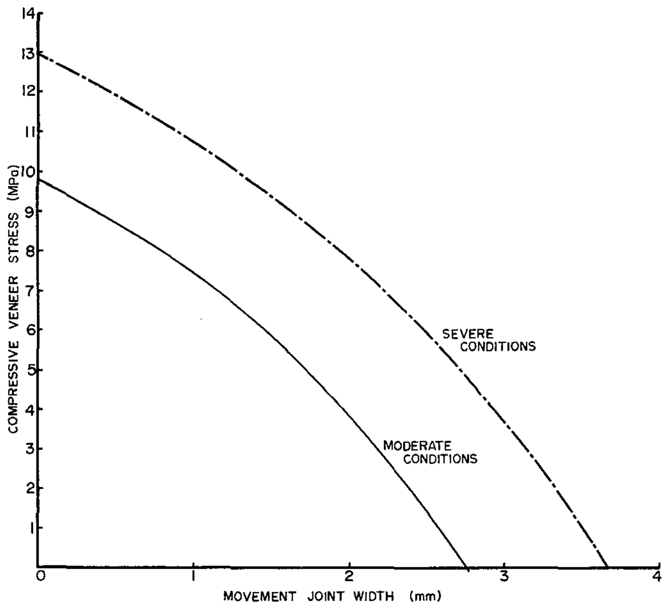

FIG. 6. Effect of movement joint width on ground level veneer stress.

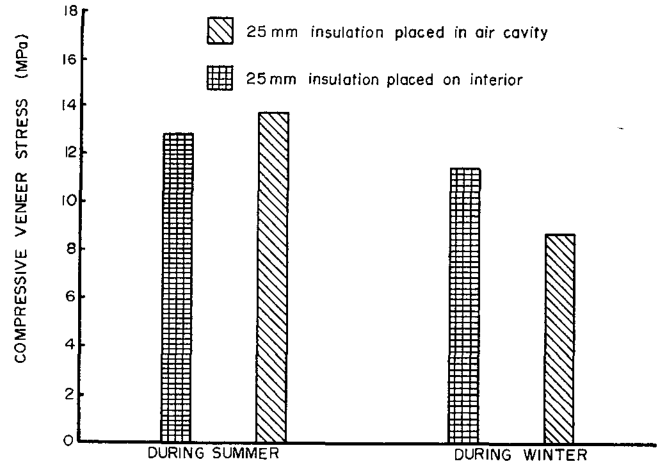

FIG. 7. Effect of insulation location on summer and winter veneer stresses under severe conditions.

in brick overhang can lead to three distinct modes of veneer failure or distress. These modes, along with their corresponding brick overhangs, are illustrated in Fig. 5. For the small brick overhangs of condition A, loads from above are supported by a narrow mortar joint, which concentrates the stress at the face of the brick and may result in spalling. For example, if the mortar is provided over one-quarter the brick width, then the local stress will be four times the average masonry stress. Based on a masonry compressive strength of 20 MPa, the point at which the average predicted veneer stress, combined with this stress concentration factor, is sufficient to cause failure has been shown in Figs. 3 and 4 for two different overhangs. Note that spalling of the brick surface, given a 25 mm overhang, is likely to occur in under 1 year for moderate conditions and in 4 months for severe conditions.

When the brick overhang is very wide, as shown by condition C in Fig. 5, the shelf angle is less restrained against rotation as it deforms, particularly if improper or excessive shimming is used. This rotation can lead to:

—local crushing at the interior edge of the masonry,

—lateral thrust on the masonry, which increases its instability and may cause buckling—the absence or poor anchorage of ties in the region of the shelf angle worsens this situation.

Condition B in Fig. 5 shows what is considered to be a normal overhang. High veneer loads may result in crushing of the mortar in the joint but the stress concentration is insufficient to cause spalling or cracking of the brick. Once the mortar has crushed, the joint begins to act as a movement joint, allowing stress relief to take place.

Of the three failure modes, condition C, or the wide overhang, is the least safe, as it can result in a buckling or bulging failure with little or no warning. Conditions A and B are stable, with condition B giving the least visible distress.

The type of backup used can also contribute to the instability of the veneer when inadequate movement joints are present. The relatively more flexible metal stud backup system, as compared with concrete masonry backup, will allow the panel to bow more readily between shelf angles. This bowing effect will tend to relieve the stress concentration at the toe of the shelf angle but may lead to a number of other, perhaps more serious, problems:

—Resultant cracking of the masonry makes the wall more permeable to water infiltration.

—Ties can be loaded excessively and their failure can be catastrophic.

—If the panel bows inwards, as is likely, owing to eccentric loading through the mortar at the shelf angle toe, the horizontal reaction from the steel stud backup tends to slide the masonry outwards off the shelf angles—this type of distress may appear as bulging at the shelf angle locations.

4.2 Movement joint width

As indicated earlier, there are many design considerations that can influence the magnitude of the load inadvertently transferred from the structure to the veneer. Perhaps the most important of these is the width of the soft joint provided under each shelf angle to accommodate differential movements. Figure 6 shows how the ground level veneer stress on the case study structure after 10 years is affected by changes in the width of the movement joint under all the overlying shelf angles. For the case study structure, it can be seen that the minimum joint width required to eliminate all stress from the veneer is about 3 mm/storey under moderate conditions and 4 mm/storey under severe conditions.

4.3 Insulation location

Additional trial runs were carried out on the case study building with the insulation placed in the air cavity between the veneer and the structure, to evaluate the effect of insulation location on the stresses developed in the veneer. In the actual structure the insulation was placed on the interior face of the column and concrete masonry. Figure 7 shows how the veneer stresses vary during both the summer and winter after 10 years under severe conditions. From Fig. 7 it can be seen that stresses during the summer are only marginally affected by insulation location. This is so because the thermally massive concrete and concrete masonry elements are not greatly affected by the daily temperature swings of the veneer—even if the insulation is absent.

However, during a cold spell in the depth of winter, the thermal mass of the concrete becomes unimportant and steady state conditions are approached. Thus, placing the insulation between the veneer and the structure rather than on the interior will decrease the veneer stresses by about 30%. In either case,

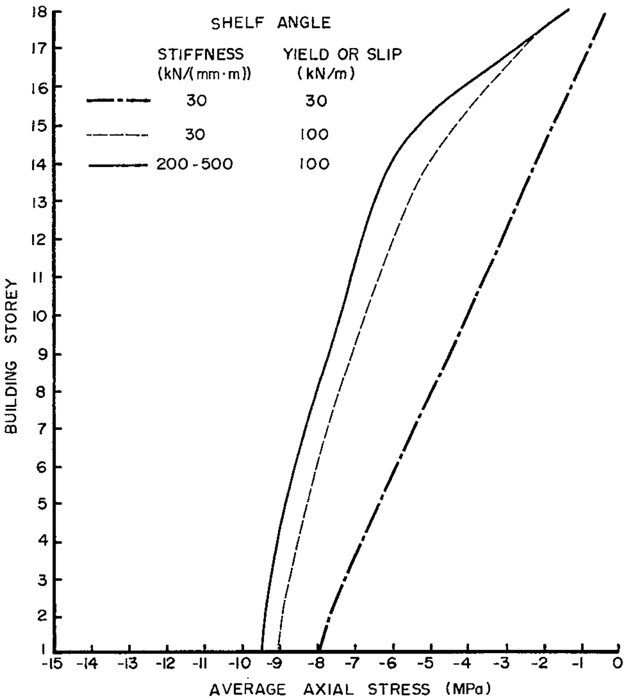

FIG. 8. Variation of veneer stress with height after 10 years under moderate conditions.

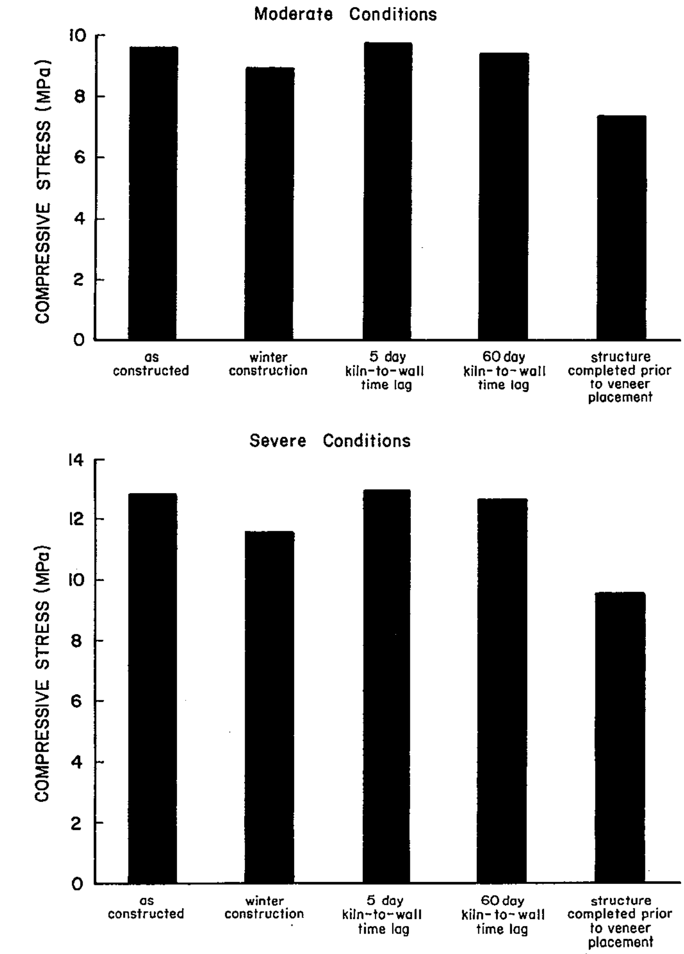

FIG. 9. Predicted ground level veneer stress after 10 years for various construction timing.

though, the summer stresses are greater than the winter stresses and so the insulation location will only have a small effect on the maximum annual veneer stress.

It should be pointed out that the insulation location can have a significant effect on stresses and deformations taking place within the structure itself. Obviously, if the exterior column is insulated from the rest of the structure and allowed to cycle through the annual ambient temperature range, then interior walls, beams, slabs, and other connections must be designed to accommodate the resulting thermal movements. From this point of view, the optimum insulation location would be between the structure and the veneer, i.e., in the air cavity.

4.4 Shelf angle stiffness

The resistance to differential movement offered by the shelf angle is dependent on the stiffness of the supporting slab or beam, the type and quality of the connection between angle and support, the amount of brick overhang, and finally, the stiffness of the angle itself. Perhaps the most variable factor is that of the connection between the angle and support. This connection can range from very stiff, as in the case study building where the shelf angles were welded to cast-in-place straps, to very flexible, as in a poor-quality bolted and shimmed connection. Bolted connections have the advantage of allowing adjustments to be made during construction but can become rather flexible if:

—bolts are not tightened properly or are missing,
—improper or excessive shimming is used,
—bolt holes are too large and (or) washers are too small.

In order for a soft joint to function properly it is important for the shelf angle to be able to carry the overlying brick panel without slipping or deforming significantly.

If, however, soft joints have not been provided and a sufficient number of shelf angles act above a given level, veneer stress has been found to be largely independent of the shelf angle stiffness and yield point. Figure 8 shows the veneer stress versus height on the case study building for three different shelf angle stiffnesses. For a constant yield or slip point, the ground level veneer stress changes by only 5% for stiffnesses ranging from 30 to 500 kN/mm per metre length of shelf angle. When the yield point is reduced from 100 to 30 kN/m (of length of shelf angle), the ground level stress is reduced more substantially—by about 15%. The shelf angles used in the case study building, with their relatively rigid welded connections, were calculated to have a stiffness of about 300 kN/mm per metre length of shelf angle.

4.5 Construction timing

The times at which the various structural elements are placed can affect the magnitude of differential movements and resulting stresses. Figure 9 shows graphically the expected ground level veneer stress on the case study building after 10 years for the following timing conditions:

(1) As constructed.
(2) Winter construction—construction beginning on November 1 rather than July 1.
(3) 5-day and 60-day lag between kiln firing of the brick and veneer construction, rather than about 30 days as constructed.
(4) Placement of the veneer after completion of the entire supporting structure, rather than the 5-level lag as constructed.

Winter construction results in larger thermal strains in both the structure and the veneer. Because the coefficient of thermal expansion of the reinforced concrete is some 25% greater than

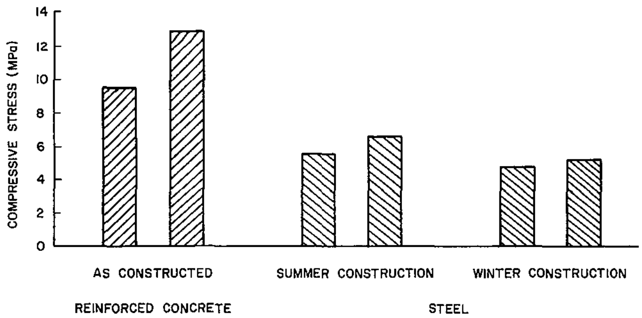

FIG. 10. Predicted ground level veneer stress after 10 years for two structure types.

that of the veneer, the column undergoes slightly larger thermal strains than the veneer. Thus the veneer stress is seen to be reduced by 7–12% when construction takes place during the winter. Note that if the insulation was placed in the air cavity between the veneer and the structure, the additional thermal strain of the column would be less than that of the veneer and veneer stresses would increase for winter construction.

As the time lag between production of brick units and construction of veneer increases, a greater proportion of the brick moisture expansion takes place prior to installation. Figure 9 shows that when the kiln-to-wall time is increased from 5 to 60 days, the expected veneer stress decreases by only about 2%. Although the corresponding decrease in the moisture expansion strain of the clay brick masonry is closer to 20%, it is only one contributing factor to differential movement.

The most significant reduction of the ground level veneer stress is achieved by delaying the placement of the veneer until after the structure is complete. This delay allows a significant portion of the creep and shrinkage of the structure to occur unhindered and results in veneer stresses some 25% lower then predicted for the case study building.

4.6 Structure type

The previous discussion has concerned itself with differential movements occurring between a reinforced concrete structure and its veneer. Steel structures also commonly employ shelf angles or shelf plates at regular intervals to support the veneer and so it is of interest to compare the two structure types. The predicted ground level veneer stresses depicted in Fig. 10 have been derived assuming the case study building to be a steel structure with dead loads and other parameters held constant. Movement of the structure is now due to elastic and thermal effects only. It can be seen that the absence of creep and shrinkage of the column reduces the veneer stresses by at least 50%. In addition, the dead loads acting in steel structures are usually less than those in reinforced concrete structures, which would further reduce the magnitude of the load transferred to the veneer when inadequate movement joints are present.

5. Repair considerations

5.1 General

Most cases of veneer distress can be directly attributed to the transfer of load from the structure to the veneer. Thus one of the primary objectives of a repair program is the provision of soft joints adequate to relieve or reduce veneer loading to an acceptable level. This is usually accomplished by removing at least one layer of brick under the shelf angle, trimming them to the appropriate dimension, and reinstalling with backup rope and caulking as a seal at the new joint.

It must be remembered, however, that the repair is being carried out on a series of highly stressed, very slender, and perhaps unstable panels. Before any work can be initiated, safety must be ensured by following a number of guidelines:
—ensure that shelf angles are adequately fastened to the structure and are able to support the weight of the overlying brick masonry,
—ensure that brick overhangs are not excessive—the masonry panel may be depending largely on the underlying masonry for its support,
—ensure that ties exist in sufficient numbers, are not corroded, and are adequately fastened to both the structure and the veneer—if the ties are badly corroded or missing, the clamping action of the shelf angles may be the important factor keeping the panel in place.

These safety checks are particularly vital if the veneer is showing signs of bulging or buckling.

In addition to the provision of soft joints, there are a number of other veneer details that affect the proper functioning of the rain-screen principle:
—Flashing and weep holes should be inspected to ensure that the water that inevitably penetrates the veneer will be drained back out again at the shelf angles—the failure of either the flashing or weep holes can lead to water entering the structure, corrosion of the shelf angles, freeze–thaw damage to the masonry, and ice lenses forming between the masonry and the back of the shelf angle, thus forcing the masonry off the angle.
—Mortar droppings on the ties and between the masonry and the structure can provide a pathway for water to reach the interior of the building and lead to premature corrosion of the ties.
—An overly flexible backup can lead to excessive cracking of the relatively stiff veneer, permitting greater water penetration.

The performance of the veneer system also depends on the geographic location of the structure. For the relatively corrosive and damp environment found on sea coasts, the use of noncorroding materials or protective coatings on shelf angles, ties, and anchors is a requisite for long-term satisfactory performance. If the veneer is subjected to freezing cycles, as is the case throughout Canada, durable clay brick units resistant to freeze–thaw would be required.

When veneer problems are associated with water penetration, the repair should include the inspection and replacement, if necessary, of damaged wallboard and insulation, particularly if these materials are exposed to the air cavity. Most wallboard will deteriorate if repeatedly wetted. Any replacement should be adequately protected against future wetting by unbroken tar paper or a similar impervious sheeting. Fibrous insulations, such as fibre glass bats, can soak up and retain large quantities of water. Not only can this result in the insulation sliding out of position but it also tends to keep the veneer and structure wet, aggravating freeze–thaw deterioration and corrosion of exposed steel. Insulation exposed to the air cavity should be of a rigid, water-impermeable type.

5.2 Types of repair

Repairs are typically carried out from the top down, relieving stress on the lower levels as the repair proceeds. The extent of repairs required by a distressed veneer system is dependent on the degree and type of distress and the condition of the shelf angles and ties. If the distress is limited to local spalling and cracking and an investigation shows that flashing and weep holes are in good condition, shelf angles are adequately secured to the structure, brick overhangs are not excessive, and a sufficient number of ties are acting, then the repair can be classified as minor — involving primarily the provision of a soft joint. The soft joints are created by removing at least one brick layer immediately below the shelf angle, trimming to the appropriate dimension, and replacing. To protect the shelf angle from the weather and to ensure the wall's function as a rain screen, the new joint should be sealed with appropriate caulking on a rope backup.

Are the new soft joints required at every level? This question is not easily answered and depends upon the stress concentration and instability factors discussed in Section 4. Note that the reduced restraint may lead to increased shelf angle rotations at the lower levels. For the case study building, maximum uniform veneer stresses are reduced to about 2.7 MPa for joints cut at every third level and to about 1.4 MPa for joints at every second level.

A typical veneer repair involves more than just the provision of a soft joint. This is so because other significant deficiencies are often present in the exterior wall system and these deficiencies must be corrected to arrive at a serviceable and safe veneer over the long term. Aside from the lack of a movement joint, deficiencies could be the following:

— shelf angles not adequately fastened to the structure due to missing or loose bolts, overcut holes or slots, and excessive or improper shimming,

— shelf angles missing or discontinuous especially at corners,

— flashing discontinuous, torn, or terminated within the veneer,

— weep holes missing or inadequate.

Repairs of these deficiencies generally involves the removal of several courses of masonry both below and above the shelf angle. One approach to accomplish this is as follows: For a given length of wall, about 50% of the veneer would be removed in pockets and the exposed portion repaired. The remaining masonry maintains support for the whole wall section. Once these pocketed portions have been restored, the remainder of the wall would be repaired in a similar fashion. Often, vertical corner cracking due to discontinuous shelf angles or inadequate vertical movement joints necessitates the removal and rebuilding of corner sections as part of typical veneer repairs.

Complete veneer replacement may be required when major deficiencies in addition to those cited above exist. These deficiencies could be:

— ties corroded, missing, or inadequately anchored,

— deteriorated wallboard, insulation, or vapour barrier,

— backup too flexible or corroded,

— extensive veneer distress in the form of spalling, crushing, cracking, buckling, or bulging over large wall areas.

Partial and even complete replacement of veneer have been necessary on a number of structures in Canada and the U.S.A. in the recent past.

Conclusions

An 18-storey reinforced concrete structure with a distressed clay brick masonry veneer was studied to evaluate the effects of various parameters on veneer stress when inadequate movement joints are provided between veneer and structure. The results of the study led to the following conclusions:

(1) In the absence of horizontal movement joints, compressive stresses in the veneer grow rapidly at first, reaching 60–65% of the 10-year values within 1 year. Stresses are reduced during the winter.

(2) Predicted uniform axial veneer stresses in the absence of a movement joint are seen to exceed the allowable code stress but are less than the expected ultimate compressive strength. Thus it appears likely that workmanship and stress concentrations effects play a major role in the veneer failure.

(3) In the absence of a movement joint, the concentration of veneer stress brought about by placing mortar at the toe of the shelf angle would result in spalling of the brick surface in less than 1 year for a brick overhang of 25 mm.

(4) The width of the horizontal movement joint or soft joint provided under each shelf angle was found to have the greatest effect on the magnitude of the compressive stresses developed in the veneer. To allow for the differential movements occurring in the first 10 years of a building's life, movement joints of at least 3 mm/storey should be provided if relatively moderate moisture movement and thermal conditions are known to exist. Based on the severe conditions assumed for the case study, movement joints of at least 4 mm/storey are required. These minimum values should be increased if the masonry is placed at the same or nearly the same time as the structure.

(5) The insulation location has a negligible effect on the maximum annual veneer stress. In the absence of a movement joint, placing the insulation between the veneer and structure can reduce the veneer stress during the winter by 30%.

(6) In the absence of a movement joint, ground level stresses are only marginally affected by shelf angle stiffnesses varying between 30 and 500 kN/mm per metre length of shelf angle. Lowering the yield point from 100 to 30 kN/m results in a more substantial veneer stress reduction of 15%.

(7) Delaying placement of the veneer with respect to construction of a reinforced concrete frame significantly reduces differential movements.

(8) In the absence of a movement joint, veneer stresses developed on an equivalent steel structure were reduced by at least 50%.

The repair of distressed veneer was discussed under the headings of minor repair, typical repair, and complete replacement. The repair was found to depend on a large number of issues in addition to the provision of a movement joint.

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