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Out-of-Plane Wind Design Loads on Inclined High-Rise Coupled Structural RC Walls

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ABSTRACT

Although most structural walls are vertical diaphragms used mainly to resist loads on the structure in the vertical plane of wall (in-plane loads), sometimes and due to architectural purposes the main structure is inclined high-rise reinforced concrete walls in which the loads affected at out-of-plane are governed the behavior of these walls. The high-rise inclined wall structures commonly have triangle shaped-structure for their stability and connected by out-of-plane elements. Detailed procedure to determine the design wind loads on high-rise inclined walls is presented based on ASCE7-05 quasi-static analytical procedure. The modeling of inclined walls subjected to out-of-plane loads versus in-plane vertical walls is discussed. Suitable finite element is selected to model the inclined walls which satisfy all freedoms of wall under different loads (gravity and lateral) and finally conclusions are listed.

Keywords: *Inclined Walls, Wind Loadings, Coupled Structural Walls, High-rise walls*

1. INTRODUCTION

The most common structural walls are shear walls in which they provided entire resistance to horizontal or lateral loads due to winds or earthquakes. Shear walls may be part of service core or a stairwell, or they may serve as partitions between accommodations. They are usually continuous down to the base to which they are rigidly attached to form vertical cantilevers. Their high in-plane stiffnesses and strength makes them well suited for bracing buildings of up to about 35 stories (123 m in height) , which simultaneously carrying gravity loading. It is usually to locate the walls on plane so that they attract an amount of gravity dead loading sufficient to suppress the maximum tensile bending stresses in wall caused by lateral loading. In this situation only minimum wall reinforcement is required. Shear walls may be planar, but are often of L- , T- , I- or U-shaped section to better suit the planning and to increase their flexural stiffness.

Sometimes the wall structure consists of walls connected by bending-resistant elements, which called coupled walls, in which the presence of the moment-resisting connections greatly increases the stiffness and efficiency of the wall system [1].

Although most structural walls are vertical diaphragms used mainly to resist loads on the structure in the vertical plane of wall (in-plane loads), Sometimes and due to architectural purposes the main structure is inclined reinforced concrete structural walls, these types of structures are commonly not for economical or structural goals but to reflect historical , community or thoughts and visions concepts , like cities entrance structures or gates, entrance structures for important areas like universities or Governmental compounds or sometimes as art symbols structures, an example is shown in Figure 1.

Figure 1. High-rise RC triangle-shaped walls structure

2. BEHAVIOR OF COUPLED VERTICAL SHEAR WALLS

The simplest description for coupled vertical shear walls is a pair of in-plane shear walls connected by bending resisting element. If the walls deflect under the action of the lateral loads, the connecting beam ends are forced to rotate and displace vertically, so that the beams bend in double curvature and thus resist the free bending of the walls as in Figure 2.

The bending action induces shears in the connecting beams, which exert bending moments of opposite sense to the applied external moments, on each wall. The shears also induce axial forces in the two walls, tensile in windward wall and compressive in the leeward wall. The wind moment M at any level is then resisted by the sum of the axial forces NL, where N is the axial force in each wall at that level and L is the distance between their centroid axes.

$$M = M_1 + M_2 + N\,L \qquad (1)$$

The last term NL represent the reverse moment caused by the bending of the connecting beams, which opposes the free bending of the individual walls. This term is zero in the case of linked walls (axial action links) and reaches a maximum when the connecting beams are infinitely rigid.

The action of the connecting beams is then to reduce the magnitudes of the moments in the two walls by causing a proportion of the applied moment to be carried by axial forces. Because of the relatively large lever arm L involved, a relatively small axial stress can give rise to disproportionally larger moment of resistance. The maximum tensile stress in the concrete may then be greatly reduced. This makes it easier to suppress the wind load tensile stresses by gravity load compressive stresses.

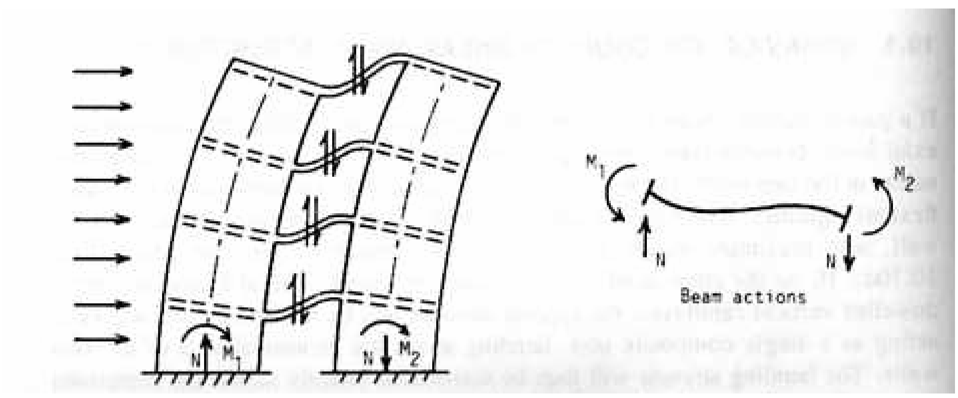

Figure 2. Behaviors of Vertical Coupled Shear Walls under Lateral Wind Loads, [1]

3. BEHAVIOR OF INCLINED COUPLED STRUCTURAL WALLS

The high-rise inclined structural walls commonly have triangle shapes for their stability and commonly connected by out-of-plane connection elements (beams or floors) at suitable elevations according to serviceability, rigidity and loads as in Figure 3.

As for vertical walls, the bending action induces shears in the connecting beams, which exert bending moments of opposite sense to the applied external moments, on each wall. The shears also induce axial forces in the two walls which effected by inclined angle θ, namely $N \sin\theta$, tensile in windward wall and compressive in the leeward wall. The wind moment M at any level is then resisted by the sum of the axial forces NL, where N is the axial force in coupling beams L is the distance between walls centroid axes at levels of coupling beams, thus also for inclined walls equation 1 is applicable, i.e:

$$M = M_1 + M_2 + N\,L \qquad (2)$$

As the same as of classical vertical structural walls , the inclined walls should resist gravity loads (dead , live and sometimes snow) and lateral loads (winds and earthquake) in which these loads produce axial, shear and overturning moment in the wall.

In vertical walls the axial loads are due to gravity loads only (dead and live loads) while shear and overturning moment are due to lateral loads only (namely winds and earthquakes). But for inclined walls the gravity loads dissolved into two components one as axial loads and another as shear and is added algebraic to the essential lateral loads (namely winds or earthquakes) thus for inclined walls the shear and overturning moment are greater than vertical walls, thus its suffer from failure hazards more than vertical walls that have the same elevation and subjected to the same lateral loads.

The simplest modeling of inclined structural RC walls coupled by out-of-plane elements can be achieved by using analogous fame model, in which the inclined structural walls are represented by an equivalent inclined frame member at the centroidal axis, to which is assigned the axial rigidity EA and flexural rigidity EI of the wall. The out-of-plane connections are represented as beams with their actual rigidity. Thus by analogous frame model the inclined coupled walls are reduced to a simple frame with very strong and rigid inclined members (walls) and flexible coupling beams.

For more accurate analysis and with availability of many structural softwares packages, the modeling of structural walls by finite element meshing is more appropriate. The simplified analogous frame model may be used to check the results or for roughly analysis.

In finite element modeling, the inclined walls are represented by bending plate element and the connected elements are represented by beam elements.

4. VERTICAL COUPLED WALLS VERSUS INCLINED COUPLED WALLS

In vertical coupled structural walls, the connection elements (beams or floors) is used to increase lateral stiffness and reduce maximum stresses in the walls , if these connection elements are removed then the walls still stable and could resist moderate loadings. Vertical coupled shear walls mainly used to resist lateral loads in their plane (lateral loads parallel to their length) thus the connection elements are linked these walls in their plane at rigid connections (in-plane connections).

In case of special coupled inclined walls structures the connections are used mainly to provide the stability of structure in additional to increase stiffness of walls. In coupled inclined wall structures (like triangle-shaped structures) the walls have large rigidity in their plane but have less rigidity and stability in out-of-plane. The sever case in inclined walls is when the lateral loads affect on out-of-plane of walls which produce with shear components of gravity loads the critical overturning moment. Thus the connection elements in the case of inclined walls are linked the walls in out-of-plane to increase rigidity and stability of walls in that direction.

The connection points between beams or floors and two walls in the case of in-plane connecting are rigid connection due to large rigidity of walls in comparison with connecting elements rigidity. But in case of out-of-plane connection the connection not rigid and the connection lines or points should be checked for one-way shear (beam shear) and two-way shear (punching shear), namely similar to flat plate slab supported on columns or walls, Figure 3.

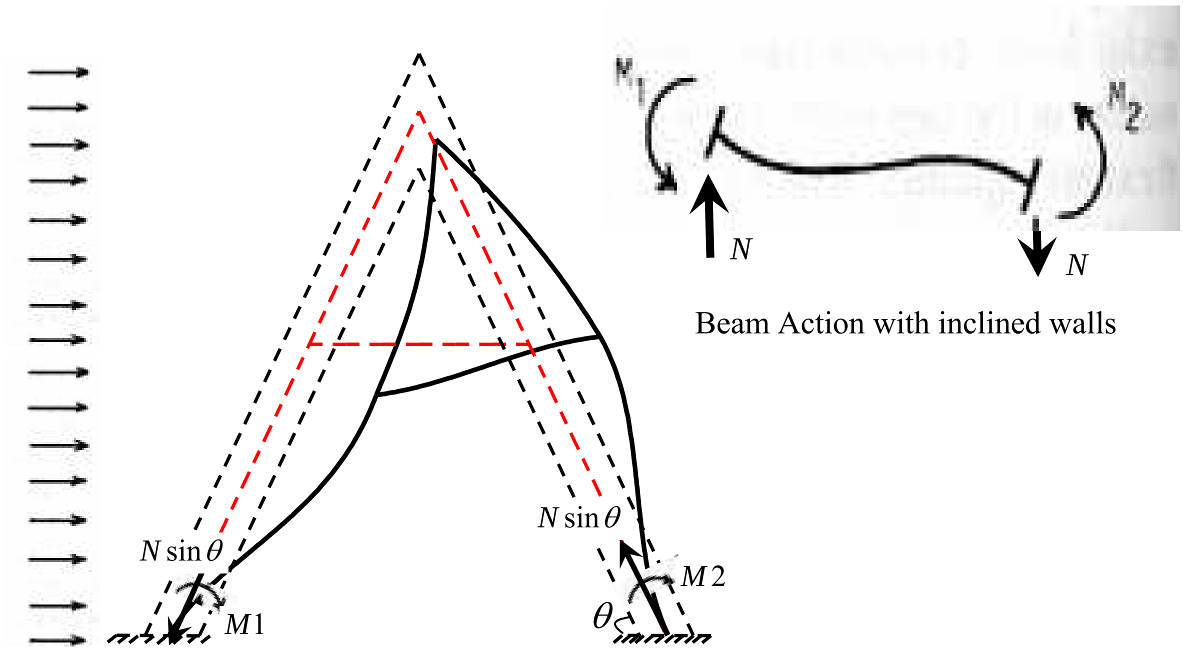

Figure 3. Behaviors of Inclined Coupled Structural Walls under Lateral Wind Loads

5. WIND LOADINGS ON WALL STRUCTURES

In practical design wind and earthquakes may be treated as horizontal or lateral loads. Although wind and seismic loads may have vertical components, these are generally small and readily resisted by columns and bearing walls. [2].
Because wind loads are considered horizontal forces, wind pressure, for design purposes, should be assumed to be applied to the gross area of the vertical projection of that portion of the building above ground. In any case, wind loads should be considered to act normal to the exposed building surfaces. Furthermore, wind should be considered to be likely to come from any direction unless it is known for a specific locality that extreme winds may come only from one direction. As a consequence of this assumption, each wall of a rectangular building should be considered in design to be subjected to the maximum wind load [2].

ASCE7-05 [3], presents three approaches to determine the design wind loads on different buildings or structures:

Method 1: Simplified Procedure (Static approach)
Method 2: Analytical Procedure (Static approach)
Method 3: Wind tunnel procedure (Dynamic approach)

Choice of any one from above methods is depend on the structure properties and surround environment characteristics. In general, static approaches are appropriate for all buildings and structures except for buildings or structures that have geometrically complex shapes, or slender or vibration-prone or subjected to sever environment conditions. For these exceptional cases dynamic approach should be used [4]. Analytical approach (method 2) is the most suitable approach to determine the design wind loadings on high-rise concrete buildings in south of Iraq, as method 1 is limited to low rise buildings only.

5.1 Wind design Loads on Inclined Wall Structures by Analytical Procedure-ASCE7-05

In all codes wind speed is used to calculate the pressure of wind on structures, which called velocity pressure q which is determined based on Bernoulli's equation. For design purposes the velocity pressure at any height z is calculated by the following equation (ASCE7-05):

$$q_z = 0.613\ K_z\ K_{zt}\ K_d\ V^2\ I \qquad (N/m^2) \quad (V\ in\ \ m/s) \qquad (3)$$

Where
V=based wind speed, which corresponds to the 3 second-gust speed at 10 m above ground in open terrain.
$K_z =$ Velocity Pressure Factor, this factor reflects the variation of wind speed with elevation and with roughness of site ground, and could be determined using Table 6.3 of ASCE7-05.
$K_{zt} =$ Topographic Factor, it's determined from Fig 6-4 of ASCE7-05. For flat terrain areas this factor equals to unity , $K_{zt} = 1$.
$K_d =$ Wind Directionality Factor, it is determined from Table 6-4 of ASCE7-05. This factor is taken equal 0.85 for inclined wall structures (triangle-shaped), i.e. $K_d = 0.85$
$I =$ Importance Factor, it is determined from Table 6-1 of ASCE7-05 which depends on building category. Inclined wall structures could be classified in Class II, thus I = 1.0.

5.2 Design wind Pressure, p

The dynamic effects of wind are accounted in the equation of design wind pressure through apply the gust factor G. To determine gust factor it should specify whether the structure is rigid or flexible. In design calculations, the structure is assumed rigid if the ratio of height-to-least horizontal dimension (width) not exceeding 4, [5], i.e, if

$$If \quad \frac{H\ (Height)}{B\ (Width)} < 4 \qquad \rightarrow \qquad Rigid\ \ Structure \tag{4}$$

For the present type of wall structures it could be assumed as rigid structures in most cases. According to ASCE7-05, for Rigid Structures

Gust Factor = G = 0.85

In the design procedure of ASCE7-05, the structural parts or system considered as:

a- Main Wind-Force Resisting System , MWFRS
Defined as the assemblage of structural elements assigned to provide support and stability for overall structure (namely the main frame of building).
b- Components and Claddings C & C :
The secondary elements of the building envelope that do not qualify as part of MWFRS like parapet , glass and plastic sheets used in windows, doors and skylight.

The design wind pressures in both cases are calculated as below:

5.3 Design wind Pressure for MWFRS, p

For rigid buildings the design wind pressure is determined from the following equations:

1- For Windward Side:

$$p = q_z * G * C_p - q_h * GC_{pi} \tag{5}$$

2- For Leeward side, Side walls and roofs

$$p = q_h * G * C_p - q_h * GC_{pi} \tag{6}$$

Where

$q_h = q_z$ evaluated at $z = h$

G: Gust effect factor

GC_{pi}: Internal pressure Coefficient, which is determined from Table 6-5 of ASCE7-05, this table depends on building enclosure classifications, namely open, enclosed or partially enclosed. Inclined walls structures are commonly consider as enclosed buildings for which $GC_{pi} = \pm 0.18$

C_p: External Pressure Coefficient, This factor determines from Fig 6-6 of ASCE7-05, in which fives values for C_p are presented as applicable, namely C_p for Windward walls, C_p for Leeward walls, C_p for Side walls, C_p for Windward roofs, C_p for Leeward roofs.

5.4 Design wind Pressure for Components and Claddings, p

Design wind pressure on components and claddings for enclosed high-rise buildings is determined from the following equations:

1- For Windward Side:

$$p = q_z\ (GC_p) - q_h\,(GC_{pi}) \tag{7}$$

2- For Leeward side, Side walls and roofs

$$p = q_h\ [GC_p\ -\ GC_{pi}] \tag{8}$$

Where

$GC_p =$ External Pressure Coefficient, which determines from Fig 6-17 of ASCE7-05 for $\theta \le 10^o$, and from Fig 6-11 of ASCE7-05 for $\theta > 10^o$, these figures depends on effective wind area that is bounded by the distance a. The distance "a" is determined from the following:

$$a = 0.1 * L \tag{9}$$

$$a = 0.1 * B \tag{10}$$

$$a = 0.9\ m \tag{11}$$

Use the larger value. The effective area for the components and claddings panel is the span length multiplied by an effective width that need not be less than one-third the span length [ASCE], i.e.

$$A = L_{C\&C} * B_{C\&C} \tag{12}$$

$$A = L_{C\&C} * \frac{L_{C\&C}}{3} \tag{13}$$

Use the larger value

5.5 Average Wind pressure

Loads must also be calculated for positive and negative internal pressure. In design pressure equations above, its clear that for each value of C_p there are two values for GC_{pi} , thus at any level these equations present two values for design pressure p. For design practice the average value of these two values p_{ave} is used to calculate wind force F, i.e.:

$$p_{ave} = \frac{p(+GC_{pi}) + p(-GC_{pi})}{2} \tag{14}$$

But for all wind pressure equations it should:

$$p \ge p_{\min} \quad , \quad p_{\min} = 0.48\ KN/m^2 \tag{15}$$

6. WIND ACTIONS ON INCLINED WALL STRUCTURES

To find wind design loads on any structures, it should consider all possible directions that winds may be blown on the structure and then the critical situation must be consider in the design.
For the case of inclined wall structures the wind loadings also should consider in all directions. In this case there are two actions of wind on these structural walls, i.e.:

1- Out-of-plane wind action
2- In-plane wind action

As in Figure 4, the in-plane wind action not represent the critical situation and could be neglected due to high rigidity of walls in their plane and smaller wind forces due to small projected area that in-plane wind faced. While the out-of-plane action represents the most critical situation, therefore the present study focused on this action.

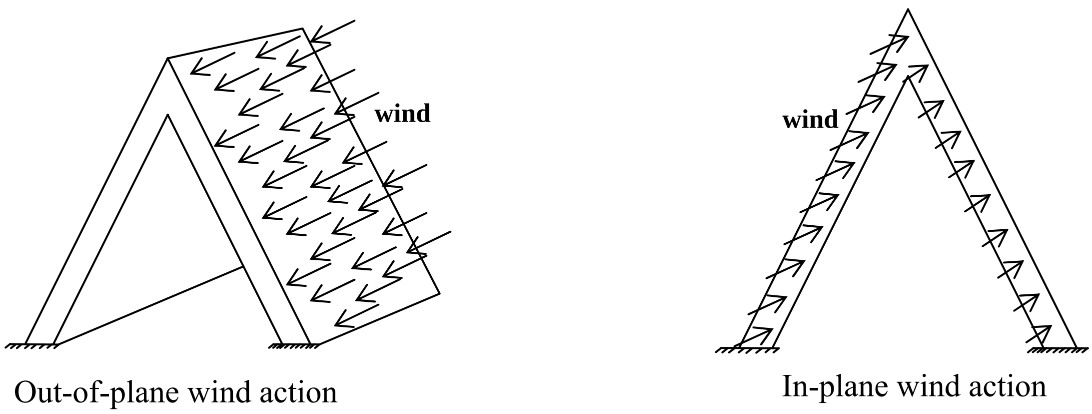

Figure 4. Wind actions on inclined structural walls

6.1 Out-of-Plane Wind design loads on Inclined Structural Walls

As mentioned in section (5.2), the ASCE7 procedure to calculate wind loads on structure, the structural parts or elements should divide into two systems:

a- Main Wind-Force Resisting System, MWFRS
b- Components and Claddings C & C

In present study of inclined structural walls, it should specify whether these walls are treated as MWFRS or C&C. Its clear that the structural walls are considered as MWFRS. But if we suppose that the wall in windward side receives the wind pressure directly and transfers the forces to the well in opposite side through the coupling elements. In this assumption, the windward wall is considered as C&C and transfers the forces to opposite wall that is served as MWFRS.
As a result, the inclined structural wall system should be analyzed separately as MWFRS and again as C&C, for each load cases and the worse case must be consider in the design.
Wind load on structural frames is divided into two parts [6]

a- Horizontal wind load (windward and leeward)
b- Roof wind loads (uplift)

Thus for any structure the wind loads must be calculated for the roofs and walls. Inclined structural walls may be considered as inclined walls and thus the pressure coefficients correspond to wall must be used. Also, it could be consider that these triangle-shaped wall structures a gable roof without vertical elements as in Figure 5, if so, thus the walls should be considered as roofs inclined with angle θ, and the pressure coefficients correspond to roofs must be used in wind loadings calculations.
Therefore, for comprehensive analysis, the walls should be analyzed independently as walls and again as roofs, and the critical cases must be considered in the design.

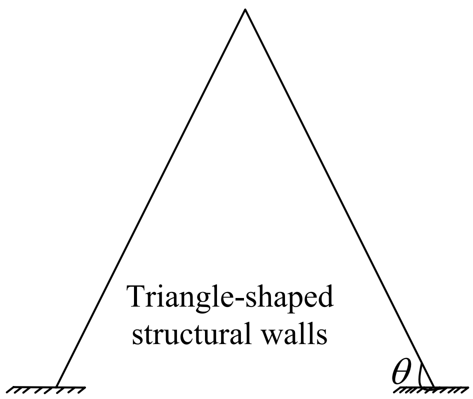

Figure 5. Triangle-shaped structural walls versus gable roof frame

6.2 Design Wind Load, F, on Inclined Structural Walls

In calculation of wind forces on structures, wind action direction normal and parallel to the roof must be analyzed. ASCE7-05 procedure requires that any building should be designed for wind load cases that that defined in Fig 6-9 in which CASE1 consider wind act normal to building faces, CASE 3 if the wind acts with angle on building while CASE2 and CASE3 are previous cases respectively but with torsional moment. Wind loadings on Inclined structural walls (triangle-shaped) have no torsional effects, thus in the present study only CASE1 and CASE3 are applicable as shown in Figure 6.

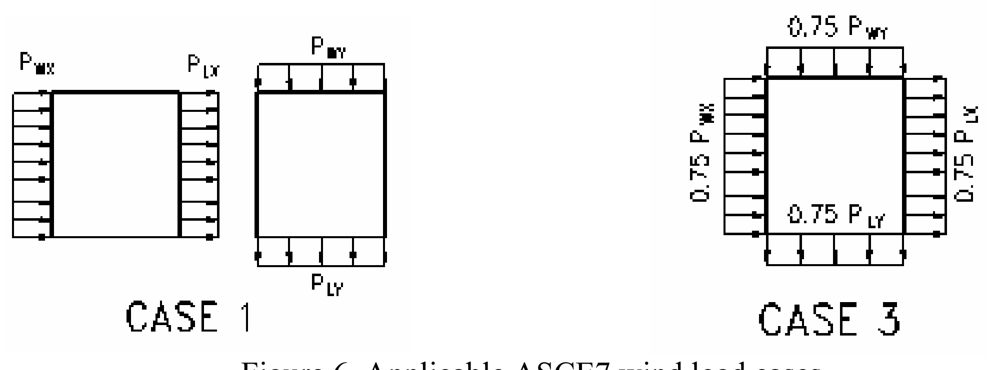

Figure 6. Applicable ASCE7 wind load cases

As mentioned in previous sections, wind pressure assumed to act normal to structure. In general the wind pressures assumed to be applied to projected area of building perpendicular to the wind direction. Thus to determine the wind forces on walls the wind pressures assumed to be applied to the gross area of the vertical projection of walls , while for roofs are applied to area of roof projection on horizontal plan, as shown in Figure 7. Thus wind forces are calculated from the following equation [6]:

$$F = p * A \qquad (16)$$

Where A is the projected area perpendicular to the wind direction. The above steps are summarized in flow chart on Figure 9.

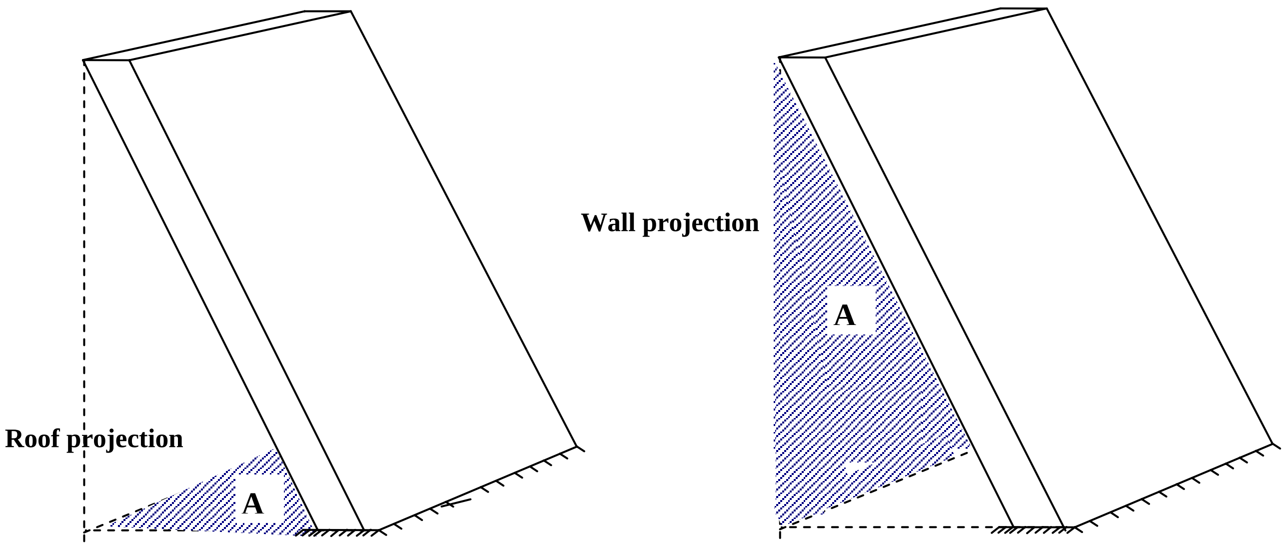

Figure 7. Projected area of walls perpendicular to the wind direction

7. LOAD COMBINATIONS

In strength design method of concrete structures, the services loads are multiplied by load factors, the possible combinations of different loads are presented in ACI-Code 2005 [7].

The major design loads of high-rise reinforced concrete buildings in south of Iraq are:

1- Gravity loads (vertical loads) , dead and live loads (and snow or rain if any)
2- Wind loads (lateral loads)

ACI Code presents four possible cases to combine above loads to find ultimate design load U as follow:

$U = 1.2(D) + 1.6(L) + 0.5(Lr \text{ or } S \text{ or } R)$

$U = 1.2D + 1.6(Lr \text{ or } S \text{ or } R) + (1.0L \text{ or } 0.8W)$

$U = 1.2D + 1.6W + 1.0L + 0.5(Lr \text{ or } S \text{ or } R)$

$U = 0.9D + 1.6W$

Where D = dead load, L = live load, Lr = roof live load, S = snow load, R =rain load and W = wind loads.

In the analysis of inclined walls the x-axis is taken parallel to wall axis and y-axis is perpendicular to x-axis Figure 8a, and the shear forces are parallel to y-axis and axial forces parallel to x-axis. Thus to find shear and axial forces due to combinations of wind and gravity loadings its should be taken into account that gravity loads are act vertically and downward while the wind act normal to inclined walls as shown in Figure 8b. Therefore gravity loads should dissolved into two components one parallel to inclined wall x-axis (namely axial force) and another perpendicular to wall (namely shear force). Thus for inclined structural walls the gravity loads produce, in additional to axial forces a shear forces. The shear component of gravity load is added to the lateral wind which increases the total shear forces in inclined walls and then increasing overturning moment.

In inclined wall subjected to lateral wind force W, and gravity dead and lives loads D and L respectively, then:

$$Axial\ Force = (D + L) * \sin\theta$$

$$Shear\ Force = (D + L) * \cos\theta + W$$

While in classical vertical walls, the gravity produce axial forces only and shear forces are due to wind only as shown in Figure 8c. Vertical wall force equation is similar to inclined walls but with $\theta = 90^o$, and above equation is rewritten as:

$$Axial\ Force = D + L$$

$$Shear\ Force = W$$

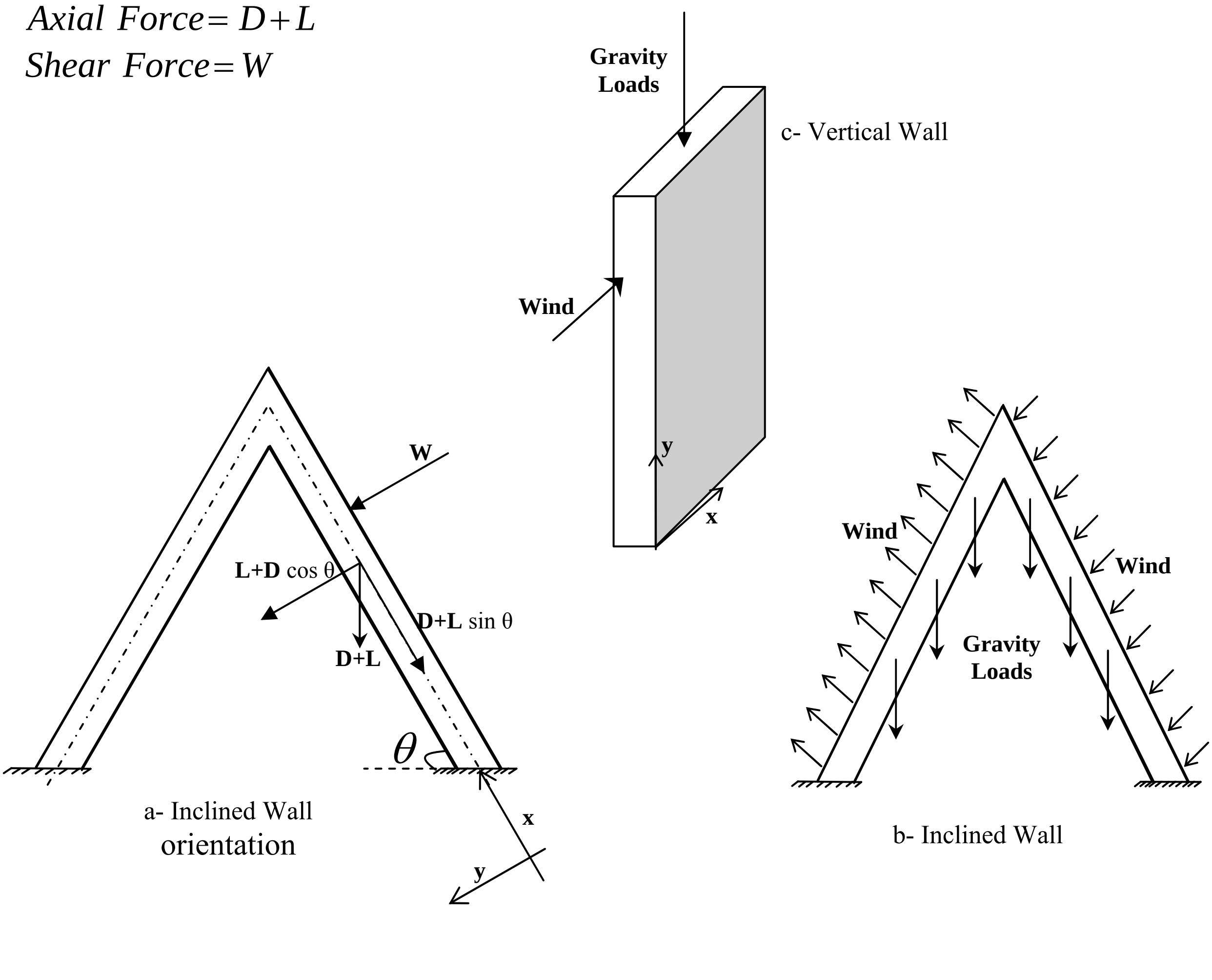

Figure 8. Wind and gravity loads combinations on vertical and inclined walls

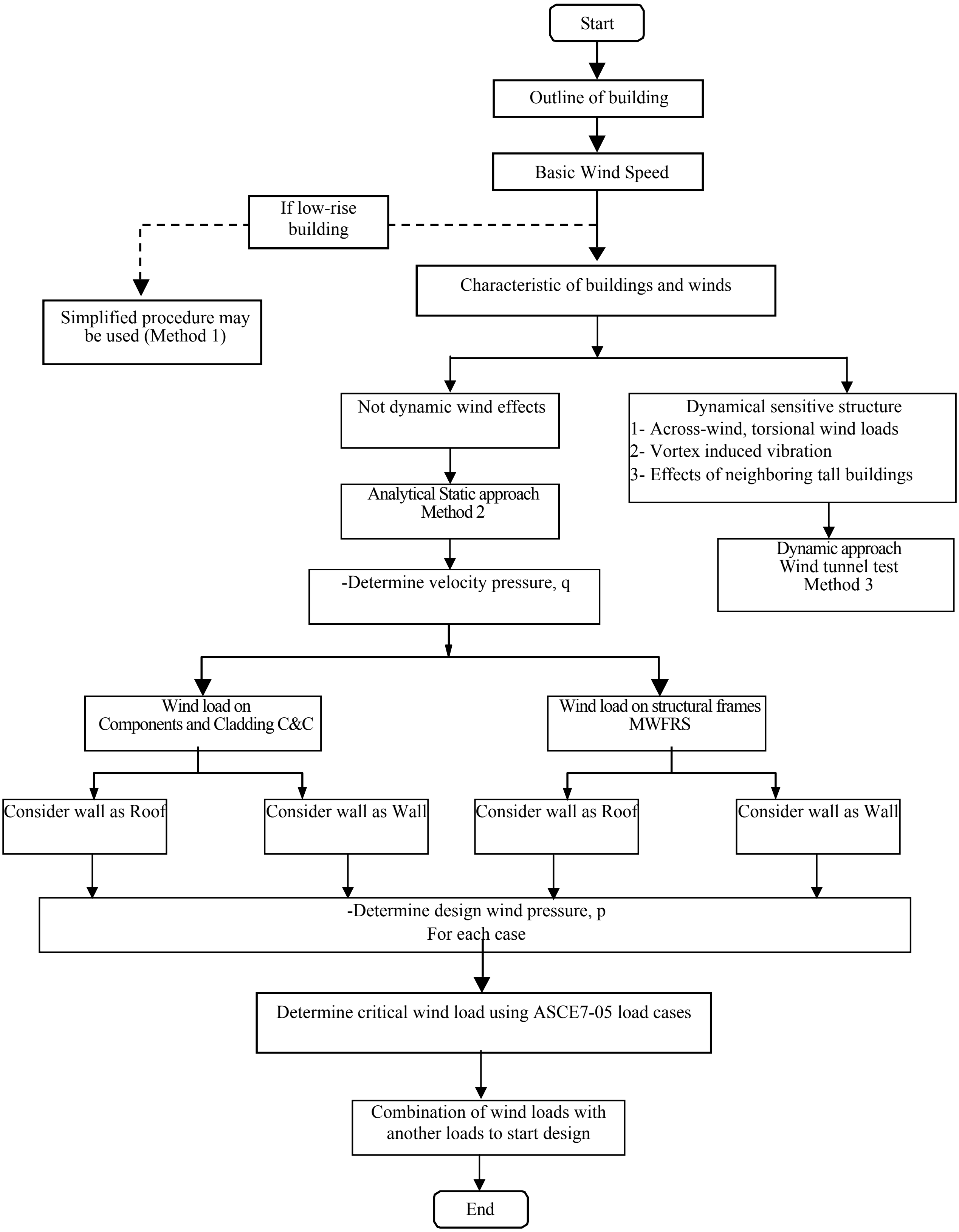

Figure 9. Flowchart of estimation the design wind load on inclined walls

CONCULSIONS

The following conclusions can be drawn:

1- The action of connections beams in inclined coupled walls is the same as for vertical coupled walls, but the axial forces in the two inclined walls (that produce due to shear in connection beams) are affected by inclined angle θ , namely $N \sin\theta$.

2- The base shear and overturning moment of inclined walls are greater than for vertical walls that have the same elevation and subjected to the same lateral loads.

3- The suitable modeling of inclined coupled walls is by represent the walls by bending plate element and the connected elements are represented by beam elements.

4- For inclined coupled walls with out-of-plane connection the connections not rigid and the connection lines or points should be checked for one-way shear (beam shear) and two-way shear (punching shear), namely similar to flat plate slab supported on columns or walls.

5- Determination of wind loads on inclined walls by analytical approach (method 2) is the most suitable approach, in which the out-of-plane wind action governs the design.

6- The inclined structural walls should be analyzed separately as Main Wind-Force Resisting System MWFRS and again as Components and Claddings C & C, for each load cases and the worse case must be consider in the design.

7- The walls (for both MWFRS and C&C) should be analyzed independently as walls and again as roofs in determination pressure coefficients , and the critical cases must be considered in the design.

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