DIAGONALLY REINFORCED SHEARWALL CAN RESIST MUCH HIGHER LATERAL FORCES THAN ORDINARY SHEARWALL

Hrista Stamenkovic*
Presenting Author: Hrista Stamenkovic

SUMMARY

This manuscript explains why Ritter and Morsch's concept for calculation of web reinforcement in a shearwall is obsolete and suggests a new idea for a much safer design of a shearwall against lateral forces. This suggestion is based on the concept of "rigidity" achieved by applying diagonal reinforcement in a shearwall. Further, this paper explains the fundamental differences between a simple beam and a shearwall and shows how diagonal reinforcement in a shearwall can greatly increase its resistance to lateral loads. It also shows that transversal reinforcement (stirrups) does not improve its resistance to cracking, while diagonal reinforcement simultaneously improves resistance to diagonal cracking and mandates ductile failure only (due to flexural tension).

INTRODUCTION

During the Alaskan earthquake in 1964, spectacular diagonal tension failure suggested that the coupling beams of shearwalls probably are inherently brittle components.[1] Even structures complying totally with the Uniform Building Code showed diagonal tension failure in such a way that no reasonable explanation emerged.[2] "Also, the relative contribution to shear strength provided by vertical and horizontal web reinforcement is not fully understood."[3]

Addition of stirrups, as calculated by the truss analogy theory, soon reaches a stage where more stirrups would not increase resistance to diagonal cracking in a shearwall: "It is not surprising, therefore, to find from experimentation that additional stirrups did not improve shear strength."[4] Or, "For the specimens with a height-to-horizontal length ratio of 1/2 and less, it was found that horizontal wall reinforcement did not contribute to shear strength."[3] For this reason of our very limited ability to design safer shearwalls, it has become necessary to prepare this study to overcome the deficiency of the existing shearwall design techniques.

THEORETICAL CONSIDERATIONS

Besides numerous other differences, the following is the main one: in a shearwall the permanent tendency to be stretched (elongated) on one of its diagonals exists, while in a beam on two supports such elongation (stretching) of its diagonals does not exist.

I. Beam on Two Supports

The author's Figure 1a clearly illustrates a law of nature that diagonal

*Building Engineer, Building Department, City of Riverside, California

cracking in a bent member is not caused by any diagonal tension, but rather by pure resultant punch shear force $V_n$, acting perpendicular to any diagonal crack. Such forces $V_n$ are caused (formed) by a combination of the following forces:

1. Vertical shear force $V_1$ caused by the support and oriented as the support itself, here upwardly;
2. Vertical shear force $V_2$, caused by the external load and oriented as the load itself, here downwardly;
3. Flexural tensile forces T, caused by flexural bending, as is shown in Figure 1a.

Obviously the resultant punch shear forces $V_n$ will be created for any type of load: concentrated, uniformed, combined, or any other type of load. As long as pure bending does not exist (where transversal forces are eliminated) the resultant punch shear force $V_n$ will always be present by combination of the vertical shear forces ($V_1$ and $V_2$) with flexural tensile forces (T), leading to diagonal cracking of a bent member.

The angle of cracking is considerably variable: for a concentrated load at some distance from a support it will be at approximately 45° from the load at the left or right side; for a concentrated load nearer to the support, it will be a straight line between the support and the concentrated load; for a uniform load, it will be at approximately 45° from a support, upwardly. For a deep beam with a concentrated load, it will be a straight line between the load and the support, while for a uniform load it will be a straight line between a support and approximately one third of the length at the top of the beam. As a result of arch creation, cracking is prevented from reaching the middle top of the span. But the angle of cracking is totally irrelevant: diagonal cracking is caused by punch shear forces $V_n$ and not by any diagonal tension as is clearly seen in Figure 1a. So by proving that diagonal cracking is caused by punch shear forces in a flexurally bent member, the fallacy of the Ritter-Morsch concept of diagonal tension is simultaneously proved, as shown in Figure 1a.

## II. Shearwall

### Description, Main Characteristics and Advantages of Author's Shearwall

The essential concept of a shearwall is "rigidity" or prevention of diagonal elongation within the shearwall. Under current shearwall design practices, horizontal stirrups are present only to stop already developed cracks, but this does not satisfy the main purpose of a shearwall which is to control rigidity and to prevent cracks from starting. In contrast, diagonal reinforcement in a shearwall as proposed herein will accomplish these two goals of rigidity and prevention of origination of diagonal, or punching (horizontal), cracks.

Yet, by preventing sudden failure of a shearwall due to shear, there is achieved simultaneously the ductility of such a member due to flexural bending, and thus the only possible failure is flexural tension failure.

<u>Diagonal tensile forces can be totally controlled by such diagonal</u>

reinforcement and by its anchorage into the foundation it will transfer such forces into the ground. Yet with such diagonal reinforcement, the total required reinforcement (including horizontal and vertical) could be the same or less than that required by the classical concept. Some mesh reinforcement is necessary to provide for needed ductility of the shearwall.

Also, two main modes of shearwall failure have been observed in experiments performed in several countries:

a) Diagonal cracking starting at a vertical edge of the wall in the flexural tensile zone and propagating diagonally therefrom;

b) If there is sufficient reinforcement at the vertical edges of the wall to prevent diagonal cracking there, then the cracking evidently will start from the top of the wall and extend towards the overturning point of the wall; this is particularly true of square or squat walls.[6]

Based on the above facts, it appears necessary to put horizontal reinforcing in the top of a shearwall to prevent diagonal cracking from starting there; there is no alternate solution to this method. Consequently, using such reinforcement as a horizontal tie, and converting the horizontal and vertical field reinforcement into two diagonal ties (one as a compressive strut and one as a tensile tie) a better shearwall will be achieved with about the same amount of reinforcing, as in the conventional theory of design as a cantilever.

The most important point is that this new design will allow the wall to react as a truss while resisting deformation under wind or earthquake loading, and simultaneously as a ductile flexural member during its mode of failure.

Therefore, where there is vibration of a building as a box, as in an earthquake, the use of diagonal bracing with the vertical shearwall edges will lead to minimal distortion and to much higher structure safety in seismically sensitive zones, such as New Zealand, Japan or California.

## III. Cracks in an RC Beam and Shearwall Compared

Diagonal cracks in a simple beam are not parallel and cannot be parallel, as Ritter suggested; rather they are always oriented from the supports upwardly on a diagonal toward the external load on the top of the beam: "At the interior support of a beam the diagonal cracks, instead of being parallel, tend to radiate from the compressed zone at the load point,"[4] or, "In most laboratory tests, if dead load is neglected, the shear span is the distance from a simple support to the closest concentrated load"[3] exactly as is illustrated by this author's Figure 1a. Yet forces located in diagonal $d_1$ and $d_2$ (Figure 1) do not exist and such a crack (following these diagonals) has never been developed in a simple beam.

Shearwalls fail diagonally as a result of stretching of one of the two diagonals ($x_1$ or $x_2$, Figure 1b). The tendency of one portion to move upwardly and another downwardly (as is the case with a beam on two supports) does not exist here! So to prevent the elongation of either diagonal, and consequently to prevent cracking parallel to the other diagonal, it is evident that diagonal reinforcement must be present because the tensile strength of concrete is almost non-existent. To prevent its pull-out, diagonal reinforcement must be anchored into the bottom and top of the wall. By adding special reinforcement at the edges of the wall ("boundary elements") and by anchoring diagonal reinforcement into the boundary reinforcement as shown in Figure 2, full and true rigidity of the shearwall will be created by the formation of statically rigid figures known as "triangles." In fact, four rigid triangles will be created, each bounded by diagonals and two boundary elements. If reinforcement is tied at the intersection of the diagonals, then four smaller auxiliary triangles will be created, each enclosed with a boundary element and portions of two diagonals.

Naturally, to prevent the overturning of a shearwall and diminished concentration of compressive forces at the overturning point (caused by dynamic impact to the shearwall at one point due to the vibrating forces of an earthquake), diagonal reinforcement must be solidly anchored into the foundation so that the entire structure would vibrate as one unit, including the foundation.

As has been stated, any additional bars of a triangle's reinforcement will lead to additional rigidity of the shearwall, consequently to additional resistance to diagonal cracking. Such strength of rigidity can be made much higher than the existing concept of the truss analogy reinforcement design! Yet, by using more diagonal reinforcement, this wall could fail only in flexural bending with the ductility of such a wall being totally preserved.

It becomes very clear that the existing concept of design of shearwalls does have a very limited possibility for increasing safety of such a wall,[3,4] while the concept of rigid triangles has an almost unlimited possibility of increasing resistance to diagonal cracking because the function of such a wall is related to the amount of diagonal reinforcement against diagonal elongation of the wall itself.

For clarity of this discussion, the rigidity of triangular reinforcement in a shearwall should be clearly distinguished from the possible diagonal bracing reinforcement done by Professor Paulay for diagonal reinforcement of a coupling beam[4,7] and from the diagonal bracing done by Gallegos and Rios as a method of repair of earthquake damaged structures.[8]

Reinforcement placed at the edges of the wall (as "boundary elements"), together with diagonal reinforcement will create (as a concept) the best possible rigidity of a given shearwall. Above all, the so-called "boundary element," with a much larger cross section than the rest of the wall, will be eliminated completely.

With the concept of possible unlimited addition of triangular reinforcement, resistance of a shearwall to possible failure could become unlimited!

## DISCUSSION

Some minimal "mesh" reinforcement should be provided to secure the shearwall as a straight plane against deflection and buckling between two floor slabs and to provide ductility, while the floor slabs of a multi-story building will provide lateral support. However, diagonal reinforcement for any concrete or masonry shearwall should become the main tool in making such a wall able to provide maximum resistance to distortion due to seismic forces leading to maximum safety of structures in seismically sensitive zones.

The same concept of rigidity could be applied for the design of spandrels (couple walls) and columns (between windows) at any concrete or masonry shearwall and make them many times more resistive to earthquakes if they are designed as independent units of a shearwall.

A shearwall which interacts with trusses in its body will show rigidity of trusses and will be able to control much higher lateral forces due to limited elongation of diagonals and proportional load distribution between the chords. Failure of a diagonally reinforced wall will be governed by the yielding of tension reinforcement located in the vertical struts (ties) at the edges of the wall. Such failure is stipulated by the frame's reinforcement at the edges of the entire wall, forcing the wall to behave as a cantilever unit at the yielding stage. In addition, horizontal reinforcement (present in the mesh) will tie the flexural compression and flexural tension zones together so that abrupt compression failure or sudden shear failure could not occur.

Evidently, an advantageously distributed reinforcement would possess the properties desired in earthquake-resisting structures: with diagonally reinforced shearwalls, overall lateral deflection and interstory drift will be controlled. Also, the limited ductility of an ordinary shearwall, caused by coupled shearwalls (short beams or columns between openings) will be totally eliminated by diagonally reinforced shearwalls. Moreover, with the diagonally reinforced shearwall and its inherent ductility, the safety of the structure itself will be fully controlled, and the enormous damage of office or apartment buildings will be greatly diminished, if not completely eliminated. It is understandable that damages would be minimal if the entire building, with its rigid shearwalls and foundation, started to vibrate as one unit or a box. Damage to the building could occur only if the structure cannot react as one rigid unit and reacts as an unstable box during seismic vibrations.

## SUBFOUNDATION

A "soft" subfoundation is essential to minimize shock to the building caused by a sudden dynamic impact of an earthquake. Such soft subfoundation should serve as a cushion between the rigid structure (box) and the supporting ground. This concept can be accomplished by a couple layers of sand and clay, isolated (separated) by prefabricated flexible plastic material (rubber-type), simulating as a whole a flexible plastic wall:

1. First layer of prefabricated plastic approximately 5"-10" thick;
2. Second layer of fine sand approximately 10"-20" thick;
3. Third layer again prefabricated flexible plastic of 5"-10" thick;
4. Fourth layer of sandy clay 10"-20" thick;
5. Fifth and last layer of flexible (plastic) 5"-10" thick;
6. The concrete foundation, rigidly fixed to rigid shearwalls, will be located directly on the plastic layer. Such a foundation during a vibration will serve as an excellent shock absorbent and reach the

concept of a floating ship on a stormy sea causing soft vibration of the rigid structure (box).

The subfoundation and foundation will be isolated on both sides by a plastic spacer (3"–5" thick) against direct contact with solid soils or rock. The higher safety of a rigid box on a softer foundation has been proven by Frank Lloyd Wright's Imperial Hotel in Tokyo where the structure withstood the Kanto earthquake (1923) while all other surrounding buildings had been heavily damaged or destroyed.[5]

## CONCLUSIONS

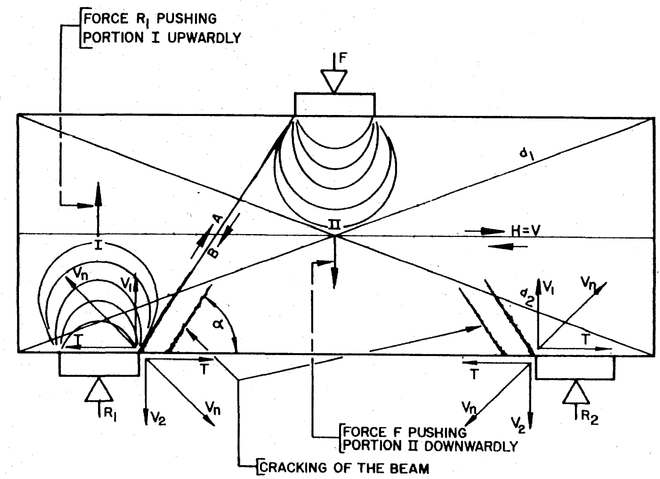
1. In a shearwall, the lateral load has a tendency to stretch one diagonal (make it longer), while in a simple beam such stretching (elongation) of diagonals does not exist;
2. Diagonal cracking in a simple beam is caused by punch shear, or by the tendency of the support to move some portion of the beam in its direction and by the opposite tendency of the external load to move its portion of the beam in its direction of action;
3. By placing diagonal reinforcement in a shearwall, any possible lateral loads can be controlled and a shearwall can be prevented from failing in shear (diagonally);
4. Reinforcement of a simply supported beam along the diagonals cannot help prevent diagonal cracking and diagonal failure;
5. Because a shearwall reinforced diagonally becomes immune to diagonal cracking, it will fail only in flexural bending by ductile failure, which is a desirable phenomenon in seismically sensitive zones;
6. The suggested new concept of a subfoundation will absorb the largest portion of shock and cause soft vibration of a rigid structure leading to a much higher safety of the structure itself.

## REFERENCES

1. Berg, V. B. and Stratta, J. L., "Anchorage and Alaska Earthquake of Mar. 27,1964," American Iron and Steel Institute, New York, 1964, p. 66;
2. Anderson, B. G., "Rigid Frame Failure," ACI Journal, Vol. 28, No. 7, January 1957, pp. 625-636;
3. Felix Barda, John M. Hanson and W. Gene Corley, "Shear Strength of Low-Rise Walls with Boundary Elements," Reinforced Concrete Structures, Publication SP-53, American Concrete Institute, Detroit, MI, 2nd printing, 1978, pp. 150-151, 154;
4. R. Park and T. Paulay, Reinforced Concrete Structures, John Wiley and Sons, New York, 1975, pp. 270, 271, 307, 308-Fig. 7.20, 611, 613, 618;
5. Roland L. Sharpe, "The Earthquake Problem," Reinforced Concrete Structures in Seismic Zones, Publication SP-53, American Concrete Institute, Detroit, MI, 2nd printing, 1978, pp. 28, 33;
6. T. Paulay, M. J. N. Priestley and A. J. Synge, "Ductility in Earthquake Resisting Squat Shearwalls," ACI Journal, July-August 1982, p. 259;
7. T. Paulay, "Earthquake-Resisting Shearwalls -- New Zealand Design," ACI Journal, May-June 1980, pp. 144-152, Fig. 1;
8. H. Gallegos and R. Rios, "Earthquake-Repair-Earthquake," Reinforced Concrete Structures in Seismic Zones, ACI Publication SP-53, Detroit, MI, 1978, p. 476, Fig. 4.

a)

BEAM ON TWO SUPPORTS




A = SHEARING (SLIDING) FORCE CAUSED BY FORCE $R_1$.
B = SHEARING (SLIDING) FORCE CAUSED BY FORCE F.
$\alpha$ = CRACKING SLOPE VARIES FROM ~35° TO ~90° (12).

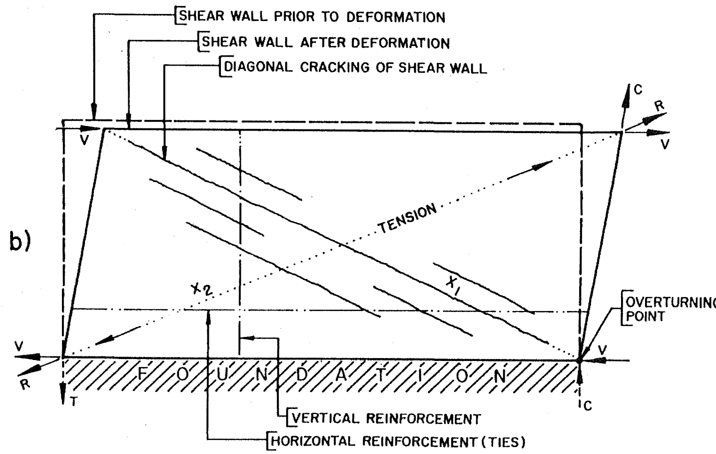
$V_1$ = VERTICAL SHEAR FORCE CAUSED BY THE SUPPORT.
$V_2$ = VERTICAL SHEAR FORCE CAUSED BY THE EXTERNAL LOAD.
$V_n$ = RESULTANT PUNCH SHEAR FORCE.
T = FLEXURAL TENSILE FORCE.

NOTES FOR BEAM ON TWO SUPPORTS:

1. CRACKS AS SHOWN ARE CAUSED BY PURE PUNCHING SHEAR OF TWO OPPOSITELY-ORIENTED FORCES AND NOT BY ANY DIAGONAL TENSION;
2. GENERALLY, CRACKS ARE ORIENTED FROM THE SUPPORT TOWARD AN EXTERNAL LOAD AS A RESULT OF PUNCH-OUT TENDENCY OF TWO OPPOSITELY-ORIENTED FORCES;
3. EVIDENTLY DIAGONAL CRACKING IS CAUSED BY A COMBINATION OF FLEXURAL TENSION (T) WITH VERTICAL SHEAR FORCES ($V_1$ & $V_2$) AND NOT BY ANY DIAGONAL TENSION.
4. THESE CRACKS ARE TOTALLY DIFFERENT FROM THE CRACKS IN A SHEARWALL BECAUSE IN A BEAM ON TWO SUPPORTS THERE DOES NOT EXIST ANY TENDENCY FOR DIAGONAL ELONGATION OF THE BEAM ITSELF;
5. IN GENERAL, CRACKING IS ORIENTED TOWARD THE CONCENTRATED LOAD: FOR UNIFORM LOAD FROM THE SUPPORT, WHILE FOR CONCENTRATED LOAD TOWARD THE LOAD.

b)

SAME BEAM AS SHEAR WALL

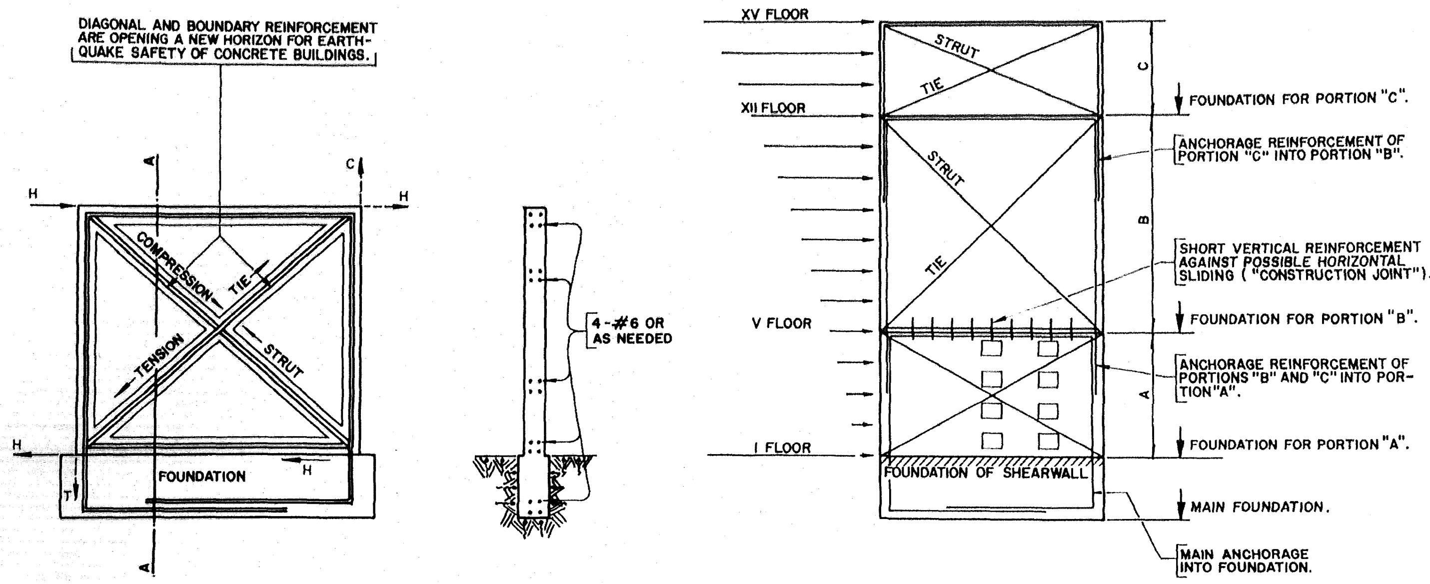



NOTES FOR SHEAR WALL:

1. THE CONCEPT OF THE TRUSS ANALOGY THEORY FOR A SHEAR WALL IS NOT APPLICABLE HERE BECAUSE TIES CANNOT CONTROL THE DEFORMATION OF A SHEARWALL (6);
2. NEITHER HORIZONTAL REINFORCEMENT (TIES) NOR VERTICAL REINFORCEMENT CAN PREVENT DEFORMATION OF SHEARWALL;
3. DIAGONAL DEFORMATION OF A SHEARWALL CAN BE CONTROLLED ONLY BY DIAGONAL REINFORCEMENT AND NOT BY HORIZONTAL TIES AS RITTER SUGGESTED, NOR BY VERTICAL REINFORCEMENT;
4. DIAGONAL REINFORCEMENT TO PREVENT ELONGATION OF EACH DIAGONAL MUST BE ANCHORED AT THE "BOUNDARY ELEMENTS" (EDGE OF WALL);
5. TO PREVENT OVERTURNING OF A SHEARWALL, DIAGONAL REINFORCEMENT SHOULD BE ANCHORED INTO THE FOUNDATION;
6. BY ADDING MORE DIAGONAL REINFORCEMENT FOR ANY ADDITIONAL EXTERNAL LOAD, RIGIDITY OF SHEARWALL COULD BE UNLIMITED, WHILE THE EFFECT OF ADDITIONAL TIES IS VERY LIMITED (6).

FIG. 1

FIGURE 1a SHOWS TYPICAL CRACKING AND FAILURE OF DEEP BEAM CAUSED BY PURE PUNCHING SHEAR, WHILE FIGURE 1b SHOWS TYPICAL CRACKING AND FAILURE OF SHEAR WALL CAUSED BY PURE DIAGONAL TENSION.




a) ELEVATION OF SHEARWALL

b) SECTION A-A

c) GENERAL EXAMPLE OF A SHEARWALL DIVIDED INTO THREE FLAT PLATE SHEAR MEMBRANES, ANCHORED INTO EACH OTHER WITH POSSIBLE PERFORATION OF SUCH PLATE WITH OPENINGS.

NOTES

1. THE CLASSICAL CONCEPT OF TRUSS ANALOGY THEORY HAS A VERY LIMITED ABILITY TO INSURE THE SAFETY OF SHEARWALLS: "IT IS NOT SURPRISING, THEREFORE, TO FIND FROM EXPERIMENTS THAT ADDITIONAL STIRRUPS DID NOT IMPROVE SHEAR STRENGTH" (6);
2. THE WRITER'S SUGGESTED CONCEPT, THEORETICALLY, DOES HAVE AN UNLIMITED POSSIBILITY FOR HIGHER RESISTANCE TO SHEAR FAILURES: FOR ANY INCREASE IN SHEAR FORCES, THERE COULD BE AN INCREASE, TO INFINITY, OF TRIANGULAR REINFORCEMENT;
3. THE CONCEPT OF "DEEP BEAM" IS NOT APPLICABLE FOR SHEARWALLS BECAUSE THE REAL LOAD OF A DEEP BEAM AND THE REAL LOAD OF A SHEARWALL ARE FUNDAMENTALLY DIFFERENT: A DEEP BEAM IS NOT EXPOSED TO ANY DIAGONAL STRETCHING, WHILE ANY TYPE OF A SHEARWALL IS EXCLUSIVELY EXPOSED TO DIAGONAL STRETCHING AND DIAGONAL ELONGATION;
4. THE STALEMATE OF PROGRESS IN GREATER SAFETY DESIGN OF SHEARWALLS IS DUE EXCLUSIVELY TO THE FOLLOWING FACTORS:
   a) THE FALSE CONCEPT OF THE RITTER-MORSCH TRUSS ANALOGY THEORY (25), AND
   b) THE FALLACY OF THE RITTER-MORSCH CONCEPT OF DIAGONAL TENSION (13-FIG. B,24).

FIG. 2

FIG. 2a SHOWS A NEW CONCEPT OF SHEARWALL RIGIDITY ACHIEVED BY TRIANGULAR REINFORCEMENT OF A FLAT PLATE CONCRETE MEMBER WHERE DIAGONAL FORCES ARE CONTROLLED BY DIAGONAL REINFORCEMENT.

FIG. 2b SHOWS A CROSS SECTION OF SUCH A WALL WITH "BOUNDARY REINFORCEMENT" AT THE TOP AND BOTTOM, DIAGONAL REINFORCEMENT, AND FOUNDATION REINFORCEMENT.

FIG. 2c SHOWS THAT THE ANGLES OF DIAGONAL REINFORCEMENT CAN VARY AS LONG AS RIGIDITY OF THE TRIANGLES IS ACHIEVED; ALSO THE PRESENCE OF VERTICAL REINFORCEMENT TO PREVENT SLIDING OF A FLAT PLATE AGAINST THE ONE BELOW; AND POSSIBLE ACCOMMODATION OF OPENINGS IN SUCH A WALL.