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CONCEPTS OF HOUSE STRUCTURES FOR PERMAFROST AREAS

PRELIMINARY INVESTIGATION OF THREE-POINT FOUNDATION SYSTEM

Prepared for
THE TECHNICAL RESEARCH DIVISION
POLICY DEVELOPMENT & RESEARCH SECTOR
OF
CANADA MORTGAGE AND HOUSING CORPORATION

by

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FOREWORD

This preliminary investigation into an unconventional way of supporting houses which are built on unstable ground is prompted by the very high rate of deterioration of the housing stock in the Arctic.

New housing requirements for the North-West Territories are estimated to average 250 units per year for the next decade. Present costs are of the order to $150,000 per unit representing an annual investment of $37,500,000. About 80% of these are built on permafrost.

Though life expectancy of presently constructed housing is only 25 years, it should be noted that experience indicates that many houses have survived only 15 years before requiring extensive rehabilitation, costing $40,000 each. Though presently built houses are far better insulated and more air-tight, the foundation system generally used is only a marginal improvement upon that used for the prematurely worn out units. One has reason, therefore, to look apprehensively at the investment in super energy efficient houses, when there is still likelihood of extensive damage to the structure, due to foundation movement.

The options offered to providing a firm foundation are:

- insulating the foundation area to maintain it in a frozen and stable condition. This approach is being developed in the Keewatin houses built in 1980 in the N.W.T.

- slab on grade

- improvements in footing design, selection of materials, and preparation. This is being attempted in houses constructed in Baffin Island in 1981.

- methods of supporting houses which can adapt to the unstable conditions. The most advanced of these methods uses inflatable bags. This is being experimented upon in Alaska.

- support of housing on piles driven into the permafrost.

Though each of the above has its technical and economic limitations, we are unaware of any comprehensive analysis of their respective pros and cons.

There is a further approach; that of supporting houses on only 3 foundation points. This may offer some unique benefits and certainly offers some unique design challenges. To our knowledge, this concept has not been elsewhere suggested. In light of the stability and structural requirements, does the concept hold sufficient merit to warrant further investigation? The following report provides a preliminary basis for evaluating the merits of this sixth option.

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EXECUTIVE SUMMARY

Arctic housing, supported on a three point foundation system offers the possibility of reducing damage which is frequently caused by racking of the building fabric found in conventionally constructed housing. This damage occurs due to differential foundation movement caused by movement in the active layer of permafrost bearing medium. The use of a three point foundation system poses structural problems. Overturning stability is reduced. Damage to the building fabric is a possibility due to the imposition of stresses into the building fabric, caused by the eccentric concentrated reactions of the foundation points.

Stability of a housing unit on a three point foundation with the piers located within the perimeter of the exterior walls is not adequate in extremely high arctic winds. Some form of tie down or footing ballast is required. Stability can be improved by moving the support points outside the house perimeter, by increasing the dead load of the house structure or by mobilization of the mass of the foundation. Mobilization of the foundation is the most efficient and least costly way to improve stability.

Imposition of high stresses into the structure can be accommodated either by placing the structure on a chassis to distribute the loads, or by improving the building structural elements so that the unit can act as 'a monocoque' structure. The installation of a chassis under the unit is relatively straightforward. Considerable costs would be incurred for the additional materials required to construct the chassis and for the additional material handling capability required to handle the heavy steel components. Monocoque construction technique requires further study before a conclusion can be reached as to its applicability. Detailed structural analysis of the building components is required. Construction techniques and details must be developed to accommodate high stresses imposed at the corners of the building and around other stress concentration areas, such as at doors and at windows. Procedures must also be developed to accommodate the loads and stresses occurring during construction, before the building is sufficiently assembled to act as a single stressed skin unit.

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1. CONCLUSIONS

Conventional housing units constructed on a three point foundation, with foundation supports on or inside the building perimeter are generally stable. Further definition of building weights is required, however, to determine whether tie downs are necessary in some very windy locations.

The construction of a housing unit on a three point foundation can be carried out by fabricating a conventionally constructed building on an independent chassis. This chassis would probably be constructed of structural steel. It would distribute the eccentric loadings caused by the three point foundations to the piers. Construction of a chassis having sufficient stiffness that it would ensure adequate performance would impose a significant cost penalty (perhaps up to 15%) to the construction cost of the house. Temporary shoring or bracing of the chassis would also be necessary during the construction phase to assure temporary stability of the structure.

Considerable additional research is necessary to develop 'a monocoque' structure suitable for the three point foundation system. In 'monocoque' construction, torsion is introduced into the diaphragm elements of the structure and hence transferred to the foundation. The following items require further study and development before design of 'a monocoque' structure is possible:

(1) appropriate selection of materials and structural systems.

(2) considerable improvements in material fastening techniques.

(3) architectural and structural engineering coordination.

(4) evaluation of thermal and moisture effects.

(5) determination of house shapes that lend themselves acceptably to 'monocoque' construction on a three point foundation.

2. INTRODUCTION

J.L. Richards and Associates Limited has been retained by Canada Mortgage and Housing Corporation to conduct a preliminary investigation into the feasibility of supporting Arctic housing on a three point foundation system. If appropriately designed, such housing would eliminate the internal racking and torsional problems associated with movement of the foundations located on active permafrost. Such racking frequently causes significant damage to housing structures constructed in the Arctic.

Reference data varies considerably within the range of the artic housing being considered. Parameters such as climatic conditions (wind loads etc.), building shape and interior layout are known to significantly affect the results of the investigation and are factors which vary significantly. Therefore, the investigation has been carried out more on a qualitative basis than a quantitative one.

An analysis has been carried out on three specific building configurations to determine the preliminary feasibility of such a foundation system and to provide recommendations as to future research areas. These building configurations have been based on two structural system which could be suitable for a three-point foundation.

These structural systems considered were:

.1 Chassis construction - a system with a separate structrally rigid frame, supporting a conventionally constructed building, and supported directly on the three foundation points.

.2 Monocoque construction - a "stressed skin" approach utilizing the natural rigidity of a box structure. Floor, roof and wall diaphragms distribute loads directly to the foundations without the need for independent structural framing external to the diaphragms.

3. BACKGROUND

At about the time this study was undertaken, a geotechnical engineering firm, H.Q. Golder Associates Limited, was retained to make general recommendations for foundations on permafrost which would accommodate a three point support system for residential construction. They have produced a report, #811-2043, entitled Report to Canada Mortgage and Housing Corporation - Engineering Consultation Proposed Housing Units Baffin Island. In the report three alternative foundation types for arctic housing are proposed: standard pad, modified pad and piles. For the standard and modified pad foundations, recommendations are put forward for construction procedures and for design considerations which would reduce differential movement of the foundation pads. Estimated bearing capacities of the order to 100 kilopascals are predicted for these pad foundations. Piled foundations are discussed and noted to be free of settlement problems; but are subject to lack of availability of equipment for installation in remote regions of the Arctic.

In the past, residential housing units in the Arctic have generally been constructed on foundations consisting of either timber cribs, or concrete pads. The foundations are underlain by a gravel bed placed on the permafrost. They are placed in longitudinal rows under the building spaced at about 2 to 3 metre centres. One row of supports is located near the centre of the structure and outer rows support the exterior walls. Movement of the foundation supports takes place horizontally and vertically as variations occur in the active layer of the permafrost or as freeze-thaw cycles take place in the granular mat which is inadequately drained. Of particular significance is vertical movement of individual foundation units. Settlement or heave of any individual foundation unit relative to a neighbouring unit causes racking of the building structure.

Racking of the building causes distress at corners and other stress concentration areas. The result is damage to cosmetic finishes, cracking of windows, failure of air-vapour barriers, and opening of cracks. Maintaining the integrity of an air-vapour barrier in buildings in the arctic climate is extremely important, as large vapour pressure differences exist between the interior heated space and the outside climate. The transmission of water vapour through failure areas results in interstitial condensation. This deteriorates insulation values, causing loss of considerable heat and possible deterioration of the structure. The opening of cracks permits cold air infiltration, rain or snow infiltration, and exfiltration of interior warm humid air. High winds cause cold air infiltration through cracks and can resulting in considerable heat loss from the building, as well as discomfort.

Buildings constructed on conventionally constructed pad foundations can be re-levelled quite easily by jacking or wedging the building frame against the foundations. However, the resulting damage to the components of building envelope, such as air-vapour barriers tears and corner cracks are difficult and costly to repair properly. Foundation movements are also likely to occur on an annual basis, resulting in a continuing requirement for maintenance. A most significant limitation to the practice of conventional construction of arctic house foundations is that the requirement for corrective action only becomes apparent after damage has occurred.

The three-point foundation study is based on the premise that three-points always define a plane, and therefore differential movement of any one support, with respect to the others, will not cause the house floor to be racked out of plane. Consequently no additional racking or torsional forces are applied to the building envelope. This can be summed up in the adage "A three - legged stool never rocks".

4. ANALYSIS

4.1 General

The quantitative portion of the analysis considered the overturning stability of a housing unit, considered as a rigid body supported on three piers. The qualitative analysis examined the effects on the internal structure caused by racking or torsion on the three point foundation, were then examined.

The three building configurations considered during the stability analysis were:

1) 9.1 m X 7.3 m one storey unit (Frobisher Bay)
2) 9.1 m X 7.3 m two storey unit (Frobisher Bay)
3) 13.4 m X 9.8 m one storey unit (Cape Dorset-unit #4)

4.2 Loads

For the purpose of the stability analysis, loads which could be imposed on Arctic housing were derived from the 1980 National Building Code:

1. wind
2. snow
3. self-weight
4. occupant loads
5. miscellaneous loads

In artic regions, wind loads are significantly higher than in most other areas of Canada. For example, in Ottawa the velocity pressure based on a 30 years return period is .37 KPa, compared with .69 KPa in Frobisher Bay, and up to 1.59 KPa in Coral Harbour. These pressures correspond to mean hourly velocities of 86 km/hour (Ottawa), 117 km/hour (Frobisher Bay) and 178 km/hour (Coral Harbour). Wind loads were applied to the structure based on Frobisher Bay wind conditions, in accordance with the recently revised provisions of the 1980 NBC Supplement -Commentary B - Wind Loads.

It is common practice in the Arctic to allow an open space between the ground and the structure to prevent thawing of the permafrost. The 1980 NBC wind pressure coefficients for residential buildings are based on structures constructed without an opening between the structure and the ground. The use of these coefficients in the analysis therefore add a measure of uncertainty to the applicability of the results of the study. Uplift may be higher for the actual condition than the theoretical and thus resulting in an unconservative estimate of the stability.

Ground snow loads in arctic regions are generally not as high as those in many of the southern areas, but there are exceptions. The ground snow load in Ottawa is 2.9 KPa. Frobisher Bay has a ground snow load of 2.2 KPa and Coral Harbour has a ground snow load of 3.1 KPa. Snow loading does not appear to be a significant factor in the design of arctic housing with a 3-point foundation system.

The self weight (dead load) of the housing unit is a principal consideration in determining the stability of the house against overturning. The terms of reference for this study indicated the shipping weight for a single storey 9.0m x 7.3m typical housing unit, for arctic construction, to be 27,600 kg. Our calculations indicate a building weight, exclusive of furnishings, to be in the order of 14,000 kg - about half the shipping weight. The analysis has been based on our calculated dead loads, rather than the shipping weights.

The calculated dead loads are:

1) 9.0 m x 7.3 m single storey unit - 13,650 kg (133.85 KN)

2) 9.0 m x 7.3 m two storey unit - 22,700 kg (222.60 KN)

3) 13.4 m x 9.8 m single storey unit - Cape Dorset - 27,300 kg (267.71 KN)

The derivation of the dead loads is included with the detailed calculations which are submitted separately. Further study to determine more accurate housing weights would improve the reliability of the stability analysis.

Occupant loads have been considered in accordance with NBC 1980. When applied over partial areas, they create an unbalanced condition which reduces the stability of the structure. However, when considered in conjunction with dead (self-weight) and wind loads, a combination factor, $\psi = 0.70$, is applied to the combined overturning loads and the effect of the occupant load becomes less significant.

Miscellaneous loads, such as water and sewage storage tanks and furniture and appliances are realistic loads, which should be taken into account. There is some question as to whether they should be considered as dead or live loads. The large difference between the calculated building self weight and building shipping weight may be accounted for in part by the inclusion of some of these miscellaneous loads in the shipping container.

It is not unlikely for a housing unit to be vacant, and empty of furniture. In such a case, tanks would probably be empty. Therefore, for this analysis, we have neglected the effects of any miscellaneous loads. This results in conservative estimates of stability.

4.3 Stability

The stability analysis is based on the Limit States design equations in the 1980 NBC. These equations best account for the effects of overturning and stress reversal which are relevant to this study. The analysis considers a rigid-body structure on its three supports. The effect of internal stresses acting on the housing unit framing is discussed under the "Structure" section.

The loads considered are:

D = dead load

Q = wind load (including uplift effects)

L = live load (due to occupancy)

The load factors applied to these loads are:

α_D = 1.25 or in the case of overturning uplift and stress reversal = 0.85

α_Q = 1.5

α_L = 1.5

The equation of the ultimate limit states are:

(1) $\alpha_D \cdot D + \alpha_Q \cdot Q \geqslant 0.0$

(2) $\alpha_D \cdot D + \psi(\alpha_Q \cdot Q + \alpha_L \cdot L) \geqslant 0.0$

Where ψ = 0.70 is a load combination factor.

The wind acting on the structure imposes a horizontal overturning force. It also imposes a vertical uplift force caused by suction on the roof. The uplift counteracts the structures' dead load. This reduces the stabilizing moment caused by the self weight of the structure. Unbalanced live load (occupant load), applied in accordance with the building code requirements, also cause an overturning moment on a structure supported on three points. Loads and their points of application can be seen in Figures 1 and 2 of Appendix 'A'. The Figures also show the specific equations of stability applied to the structures. Overturning and stabilizing effects and factors of safety, are shown in Figure 3, 4 and 5. The detailed calculations are, however, submitted under separate cover.

The location of the support points used in the analysis is shown in Figure 1 and 2 of Appendix 'A'. The three support points have been located within the confines of the perimeter walls of the building but as far away from the centre of gravity of the building as possible. This results in the achievement of maximum stability. Spans of the floor systems are also kept as short as possible.

With the three support points of the house located on the perimeter of the house, the axis, about which the structure will overturn is about half way between the structure's centre of mass and the exterior side wall. The side wall of the house would be the axis of rotation of a conventionally constructed unit. Therefore, the resisting moment of a house supported on a three point foundation with supports located on the perimeter of the house, is approximately 50% of that of a house constructed with foundations beneath the side walls.

By locating the support points outside the perimeter of a unit, an increase in the structure's stabilizing moment can be expected if the dead weight of the structure exceeds the uplift of the wind. That is, provided the unit has a certain minimum weight for a given wind condition, the stability can be increased by moving the supports outside the perimeter of the unit. If the basic weight of the unit is less than the uplift of the wind, no change in the support conditions will improve the stability. If the net difference between the dead load and uplift is small, considerable movement of the support points beyond the perimeter walls is necessary to cause an appreciable increase in resisting moment. Similarly, if the net difference between the dead load and the uplift is large, a small movement of the support points beyond the perimeter wall, causes a large increase in the resisting moment.

Another way of increasing the stability of the unit is to increase the effective dead load acting on the structure. This can be accomplished either by generally increasing the mass of the structure of the housing unit, or by anchoring the unit to the foundations thus mobilizing the mass of the foundation. Anchorage to the foundation is more effective than increasing structure mass because the mass of the footing is located further away from the axis of rotation than the centre of mass of the structure. Good connection details are required between the foundation and the unit structure to ensure full mobilization of the mass of the foundation.

When calculated, dead loads and Frobisher Bay wind conditions ($q_{1/30}$ = .69 KN/m^2) are used to compute stability, two of the three units do not have an adequate factor of safety against overturning. Using the higher value of self-weight provided in the terms of reference (27600 kg), the single storey 9.0 m x 7.3 m unit is stable and safe.

The possible occurrence of extremely high velocity pressures at locations such as Coral Harbour and the use of non-conservative wind pressure co-efficients, and unverified self-weights of the structure, render the results of the analysis to be somewhat unreliable. To obtain a more reliable assesment of the stability, the following are recommended:

1. More accurate determination of the housing unit weights and miscellaneous loads, such as furniture, tanks, and appliances.

2. Further research into wind pressure coefficients to determine if those recommended in the 1980 NBC are appropriate for housing raised above the ground.

3. A tie down system, connecting the housing unit to the foundation, seems to be inevitable in the areas where high winds are common. The tie-downs may be similar to systems as specified for Mobile Houses in CSA Standard Z240.2.1-1979, or may utilize the mass of the foundation pads.

4.4 Structure

The three point foundation system poses problems not accounted for by conventional construction procedures and materials. Conventional wood floor joists are limited to spans of about 6 metres by strength and deflection requirements, as well as by economics. With the three point foundation, spans well in excess of 6 metres will occur.

Additional primary floor beams, or other structural components would therefore have to be installed. To avoid the need for additional primary floor framing, new materials or composite beams, or built-up sections which span further might be used to accommodate the longer floor spans. Interior bearing partitions must also be eliminated, unless primary structural members can be located directly below, to support them.

With a three point foundation system, certain elements of the structure, such as cantilevered walls, are continuously subject to high stress levels. As conventional construction has been found to be unsatisfactory, due to periodic high stresses imposed by racking of the building, design of a new structure which permanently stresses these same elements, must utilize new construction techniques or new materials to accommodate these stresses.

Two types of construction could accommodate these effects of the structure racking. The first involves construction of an independant torsionally rigid frame or chassis below the structure, to accommodate all vertical and horizontal loads, replacing the conventional foundation system. For the purposes of this report, this approach will be called a "chassis" concept. The second concept involves reinforcement or modification of the existing elements of the building structure so that the stressed shell of the unit accommodates these loads. This will be referred to as a "monocoque" structure.

To qualitively examine the effects of a house sitting on a three point foundation, cardboard models were constructed to a 1/48 scale of the single storey 9.0m x 7.3m unit. By varying cardboard thicknesses, rigidity of connections and diaphragm stiffness, the effects of torsion of a conventionally framed wood structure were modelled.

Although a cardboard diaphragm does not model the wall, roof and floor diaphragms of conventional construction particularly well in shear and flexure, it does model the torsional stiffness of these elements quite well. The cardboard diaphragm is much stiffer, in-plane, than a framed wall. High shear stiffness when compared to flexural stiffness, is a trait of the diaphragm, whereas in a framed wall, shear deflections are large when compared to flexural deflection. This is due to numerous openings for windows and doors, and to the weak connection between the sheathing to the studs in the framed walls. Shear deformations are noticed in framed walls where the plaster board breaks, or where windows twist out of alignment.

A closed box was found to be torsionally rigid; provided good diaphragm-to-diaphragm connections were made. Torsional rigidity of the elements themselves, was not a primary requirement. Rather, shear and flexure stiffness of the diaphragms contributed to the torsional stiffness. Removal of the ceiling diaphragm, the floor diaphragm or significant portions of either, allowed the box to twist significantly. Discontinuity, in any of the diaphragms, caused the rigidity of the box to become dependent on the torsional rigidity, as well as the flexural and shear rigidity of the individual diaphragms. Since it is not possible to substantially increase the torsional rigidity of a conventionally constructed wall it is therefore necessary to maintain integrity of the diaphragm elements of the housing unit by ensuring they remian connected to form a closed box structure.

As flexural and shear rigidity of the cardboard model were reduced, the box's torsional rigidity was found to be reduced. Of the two components, the shear stiffness was found to contribute more significantly than flexural stiffness, to the torsional rigidity of the box, when comparing the model to an actual housing unit.

Based on this qualitative examination of the model, it is apparent that conventionally constructed housing must be modified considerably to accommodate a three point foundation. The diaphragm elements (walls, floor and roof) of the unit will have to be constructed with the following characteristics:

1. The unit must be closed on all six sides, by the equivalent of diaphragms. That is, any substantially sized holes in the diaphragms must have a reinforced surround, to counter the weakening effects of the hole.

2. The walls, ceiling and floor must be securely connected to each other.

3. In-plane bending stiffness and shear stiffness of each diaphragm must be increased considerably, so that the stresses induced in the wall by torsional loading of the unit can be resisted with little or no deformation of the elements.

4.4.1 Chassis Concept

The chassis concept is simpler to visualize and to analyze than the monocoque system. It involves construction of a torsionally rigid frame, underneath the floor of the housing unit. This frame would distribute all loads from the unit to the three point foundation. It should be constructed so that:

1. Conventional floor joist framing can be used. The limit on conventional wood floor joist spans to about 6 metres, indicates that additional primary structural support framing must be added to the chassis, if building widths in excess of 6 metres are used.

2. Torsional stiffness is provided in the frame to resist rotations imposed by horizontal loads and unbalanced vertical loads.

3. Flexural and shear stiffness is provided for cantilevered end and side wall support.

4. The load transfer mechanism of the conventional house structure is replaced by additional primary structural members in the chassis - That is, wall loads must be supported at the perimeter of the building and under bearing partitions by beams.

5. High reactions at the three piers are accommodated.

6. Unbalanced construction loads are to be accommodated. It may be necessary to provide temporary stability to the frame during construction of the unit.

These criteria dictate the need for a strong, stiff, torsionally rigid rectangular frame, with beams to pick up bearing walls. Connections between the beams require careful detailing, to achieve the necessary rigidity.

To provide adequate torsional rigidity, the chassis must be constructed of elements having high torsionally rigidity, such as box beams rather than I beams. We have carried out preliminary calculations which indicate that such a chassis would contain a large quantity of steel. Estimated tonnages and costs are as follows:

Unit		Weight of Steel		Estimated Cost (based on $2800/tonne)
1. 9.0m X 7.3m single storey	-	2.0 tonnes	--	$ 5,400.
2. 9.3m X 7.3m two storey	-	2.65 tonnes	--	$ 7,420.
3. 13.4m X 9.8m Cape Dorset single storey	-	4.3 tonnes	--	$12,040.

Current installed prices for such structural steel are about $1400.00 per tonne for large projects in southern Canada in 1982.
Shipping costs to the Arctic would probably at least double the cost. The costs shown above assume this doubling. In some communities the weight of the chassis components might present difficulties. Cranage (or the equivalent) may be required to handle the heaviest individual components of the chassis which weigh in excess of 1 tonne.

4.4.2 Monocoque Concept

The monocoque construction technique utilizes the strength and stiffness of the existing wall and roof diaphragms to resist the loads. The diaphragms act as "stressed skin" panels. There are certain structural characteristics required of the monocoque system.

1. Torsional stiffness of the building structure.

2. New methods of connecting wall/wall, wall/roof, and wall/floor,to ensure the torsional rigidity of a monocoque structure.

3. Additional flexural and shear capacity in the cantilevered portions of the walls.

4. Development of new details to avoid crushing and local overstress at the highly loaded pier foundation reaction points.

5. Development of new floor framing techniques because floor spans are too long for conventional wood framing.

6. Development of details accounting for differential movement problems, associated with varying moisture contents in the wood structure, especially in the more highly stressed structural elements.

Increasing the torsional stiffness of the structure requires substantially increasing the in-plane flexure and shear stiffness of the wall and ceiling diaphragms. The cardboard model study indicated that it is possible to construct a rigid box with diaphragm elements that have little or no torsional rigidity themselves. This is done by providing good in-plane flexural and shear rigidity within the diaphragms and adequate connections between the diaphragms.

The modification of conventionally constructed walls, floors and ceilings into diaphragms having adequate shear and flexual rigidity, requires the fabrication of these diaphragms into the equivalent of built-up beams. These beams would have thin continuous webs secured to stocky continuous flange elements. The webs would provide shear strength, while the flanges would provide flexural strength.

The shear strength of a conventionally constructed wall, floor ceiling diaphragm is a function of (i) the strength of the connection between the sheathing elements and the studs or joists, and (ii) the location and size of the holes (doors and windows) within the diaphragm.

Increasing the in shear strength and rigidity requires an improvement of the connections used to transfer shear between sheathing units. Conventional construction techniques utilize 50 mm nails driven at about 300 mm intervals into a common stud or joist. This type of connection is not adequate for the shear transfer required for a three point foundation type housing unit. Nailed connections are a major weakness in conventional wood frame housing. Nailing is used to hold components together rather than to transfer loads; loads are generally transmitted by direct bearing of one wood element against another. Monocoque construction requires the development of a fastening system which will permit a substantial increase in shear transfer between sheathing units and joists or studs, and between diaphragm units. This may be done by increased nailing, by glueing, by screwing, by installation of connector plates, or by a combination of these techniques.

The development of flexural strength in diaphragms requires secure attachment of the web component of the "beam" to the flange component. For wall diaphragms, this involves provision of a connection between the wall sheathing and the perimeter floor joists. Conventional practice does not require fastening of wall sheathing to the floor joists. Sheathing is normally nailed to runner or cap plates, which in turn are nailed to the joists directly, or through floor sheathing. Soft materials, such as gypsum board or fibre board, are not suitable for sheathing, as they are too flexible and/or weak to carry the shear forces and to transfer forces between components of the diaphragms.

The interconnection of the diaphragms, in conventionally constructed housing, is not very substantial and is not adequate for a monocoque structure on a three point foundation. Wall to floor and wall to roof connections are made by toe nailing joists to cap plates or by nailing runner plates to the floor sheathing. Wall to wall connections often do not exist as corner studs are not always nailed together. The racking forces which would occur in these joints, in a monocoque structure on a three point foundation system, are extremely high, and would require specially designed connections at these locations.

Large door and window openings in the walls of housing units constructed as a monococque structure significantly reduce the shear capacity and the shear stiffness of the diaphragms. Reinforcement around such openings is essential. Placement of door and window openings must be done in such a manner as to maximize the wall stiffness. It must also provide room between openings for reinforcement which can reinstate lost stiffness and strength. The reinforcing concept for such large holes would be similar to the reinforcement of either an open web steel joist with a clearway, or a wide flange beam with a large web opening. Conflict between the architectural requirements of opening size and location and the structural engineering requirement for reinforcement must be resolved.

Pier reactions with a three point foundation system will be high. This will necessitate the installation of reinforcement in the walls of the housing unit to distribute the loads into the diaphragms a monocoque building. An integral steel truss within the wall to distribute the pier reactions may be required. Or, complete wall units may be fabricated as wood trusses using light gauge metal truss connector plates to fasten members together. This reinforcement might also supplement the requirements for the additional flexural strength requirement in the walls.

The floor or roof spans which occur in monoque structure necessitate either the installation of central beams under the floor or roof, to limit the span of the joist framing to acceptable lengths, or a change to a framing system capable of spanning the full width of the building. Open web wood joists, similar to those constructed for conventional prefabricated roof trusses might be a suitable alternative.

The three point foundation concept will probably utilize conventional materials, especially wood, stressed to a considerably higher level, and spanning considerably further than would be found in conventionally constructed housing. Recent experience with prefabricated roof trusses, has shown that servicablility problems are occurring due to the movements associated with varying seasonal moisture contents in the wood. These movements have had detrimental effects on the construction and it is not unlikely that such movements could occur within a highly stressed monocoque box, subject to thermal and moisture variations.

A final and most significant concern in the construction of a monocoque unit is how to account for the dead loads of the structure during construction before all components are assembled and capable of acting together as a unit. Complete shoring of all the floor, and support of the perimeter, would in all probability be required to keep the torsionally flexible components in-plane, and stable until completely fastened together to form a unit.

5. RECOMMENDATIONS

Further detailed study of the three point foundation concept is recommended.

Realistic dead-weights of the structure must be established, to enable the stability analysis to be carried out reliably.

The "chassis" system requires little further development, except refinement of costing and detailed structural design.

The "monocoque" concept would benefit from considerable additional study. The study should be limited to single storey housing, as stability problems generally occur with the two storey units. Dimensions of the monocoque building should be limited, such that reasonable spans for the conventional flooring systems are not exceeded, that is 6 to 7 metres on the least span. A detailed structural analysis of the torsional effects would be appropriate perhaps with a finite element solution modelling the components of the diaphragms, would lead to a better understanding of the loads which might be expected at the connections between diaphragms and between elements of the the diaphragms. A review of the conventional wood frame housing techniques must be made, to make modifications in the construction in the following areas:

1. better interconnection between diaphragms.

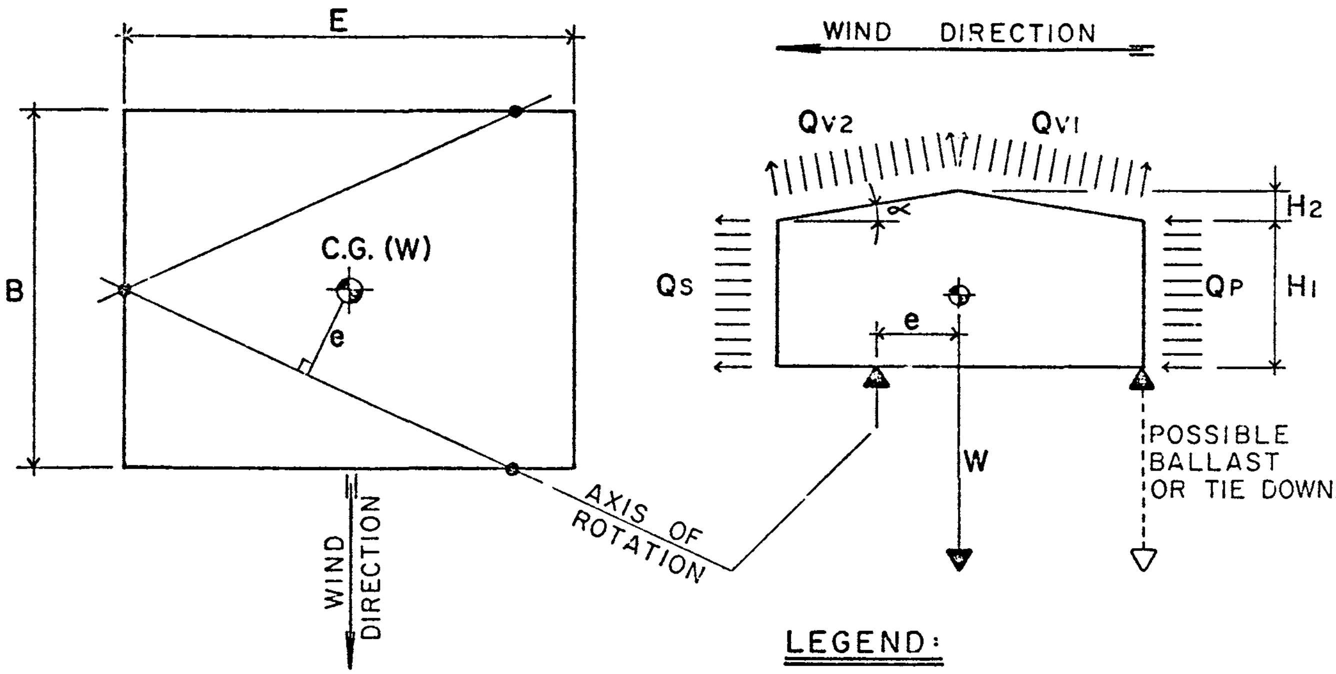
2. better shear connection between elements of the diaphragms to increase shear and flexural stiffness.

3. implementation and connection of flanged elements into the diaphragms.

Alternative construction techniques should be examined. Until these construction details have been developed for a monocoque structure, it will not be possible to rationally evaluate the economics and practicality of the concept.

APPENDIX "A"

EQUATION OF STABILITY
AND
STABILITY SUMMARY



LEGEND:

MOT........ OVERTURNING MOMENT.
MREST... MOMENT OF RESISTANCE.

EQUATIONS OF STABILITY:

WORKING:

$$M_{OT} = (Q_P + Q_S) \times \frac{H_1}{2} + (Q_{V2} - Q_{V1}) \sin\alpha \left(H_1 + \frac{H_2}{2}\right)$$

$$M_{REST} = We - \left[Q_{V2} \cos\alpha \left(e - \frac{B}{2}\right) + Q_{V1} \cos\alpha \left(e + \frac{B}{2}\right)\right]$$

FACTORED:
(ULTIMATE)

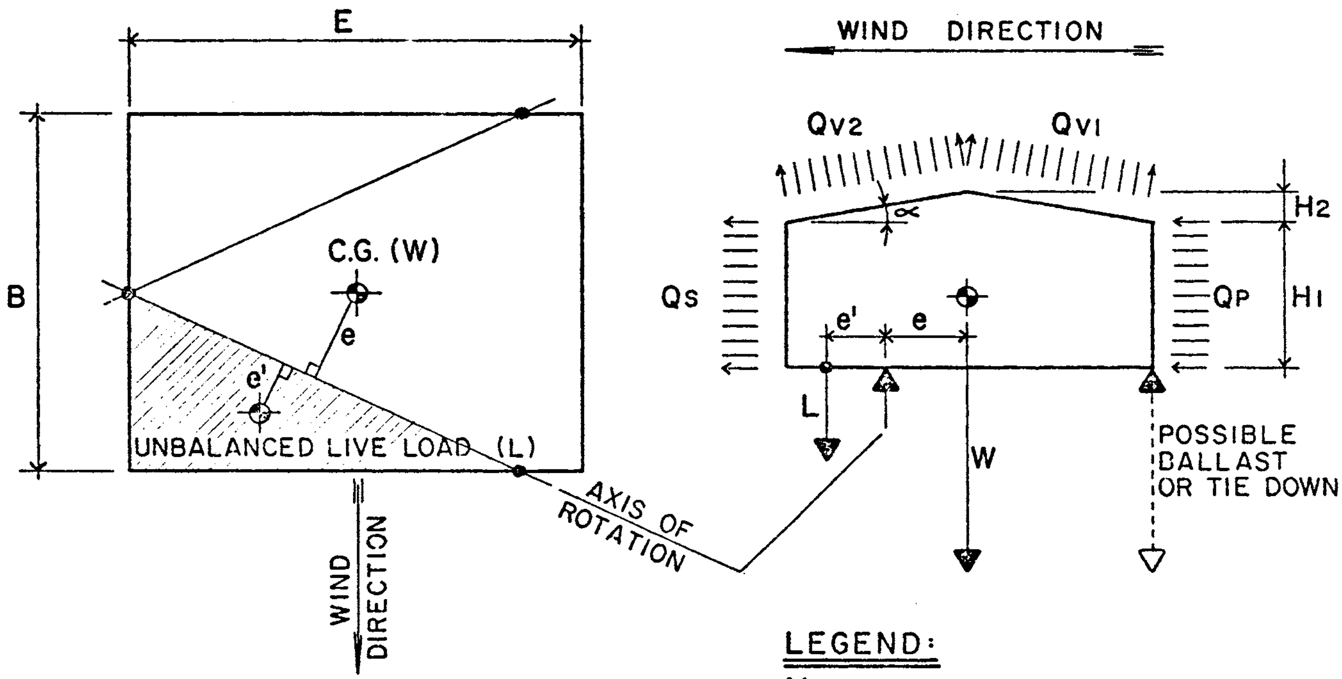
$$M_{OT_U} = 1{\cdot}5\ M_{OT}$$

$$M_{REST_U} = {\cdot}85\,We - 1{\cdot}5\left[Q_{V2} \cos\alpha \left(e - \frac{B}{2}\right) + Q_{V1} \cos\alpha \left(e + \frac{B}{2}\right)\right]$$

FACTOR OF SAFETY:
FOR LIMIT STATES TO BE GREATER THAN 1·0

$$F.O.S. = \frac{M_{REST_U}}{M_{OT_U}}$$

FIG. #1 —— CASE #1 DEAD LOAD + WIND LOAD



LEGEND:

MOT....... OVERTURNING MOMENT.
MREST... MOMENT OF RESISTANCE.

EQUATIONS OF STABILITY:

WORKING:

$$M_{OT} = (Q_P + Q_S) \times \frac{H_1}{2} + (Q_{V2} - Q_{V1}) \sin\alpha \left(H_1 + \frac{H_2}{2}\right) + Le'$$

$$M_{REST} = We - \left[Q_{V2} \cos\alpha \left(e - \frac{B}{2}\right) + Q_{V1} \cos\alpha \left(e + \frac{B}{2}\right) \right]$$

FACTORED:
(ULTIMATE)

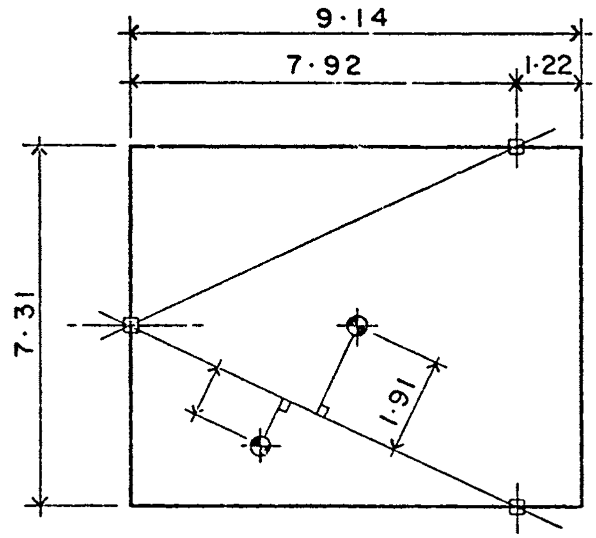
$$M_{OT_U} = .70 \times 1.5 \times M_{OT}$$

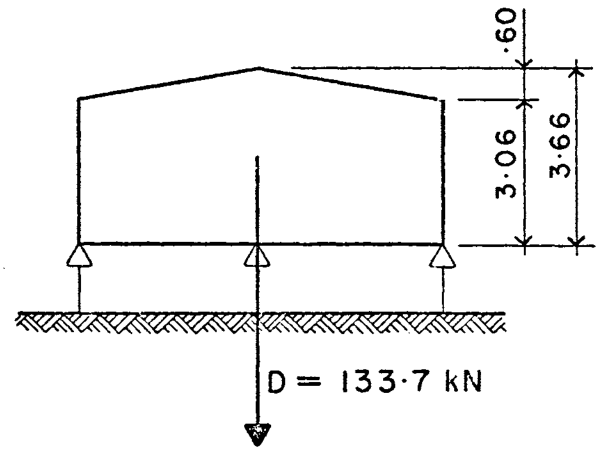
$$M_{REST_U} = .85\,We - .70 \times 1.5 \left[Q_{V2} \cos\alpha \left(e - \frac{B}{2}\right) + Q_{V1} \cos\alpha \left(e + \frac{B}{2}\right) \right]$$

FACTOR OF SAFETY:
FOR LIMIT STATES TO BE GREATER THAN 1.0

$$F.O.S. = \frac{M_{REST_U}}{M_{OT_U}}$$

FIG. #2 — CASE #2 DEAD LOAD + WIND LOAD + LIVE LOAD





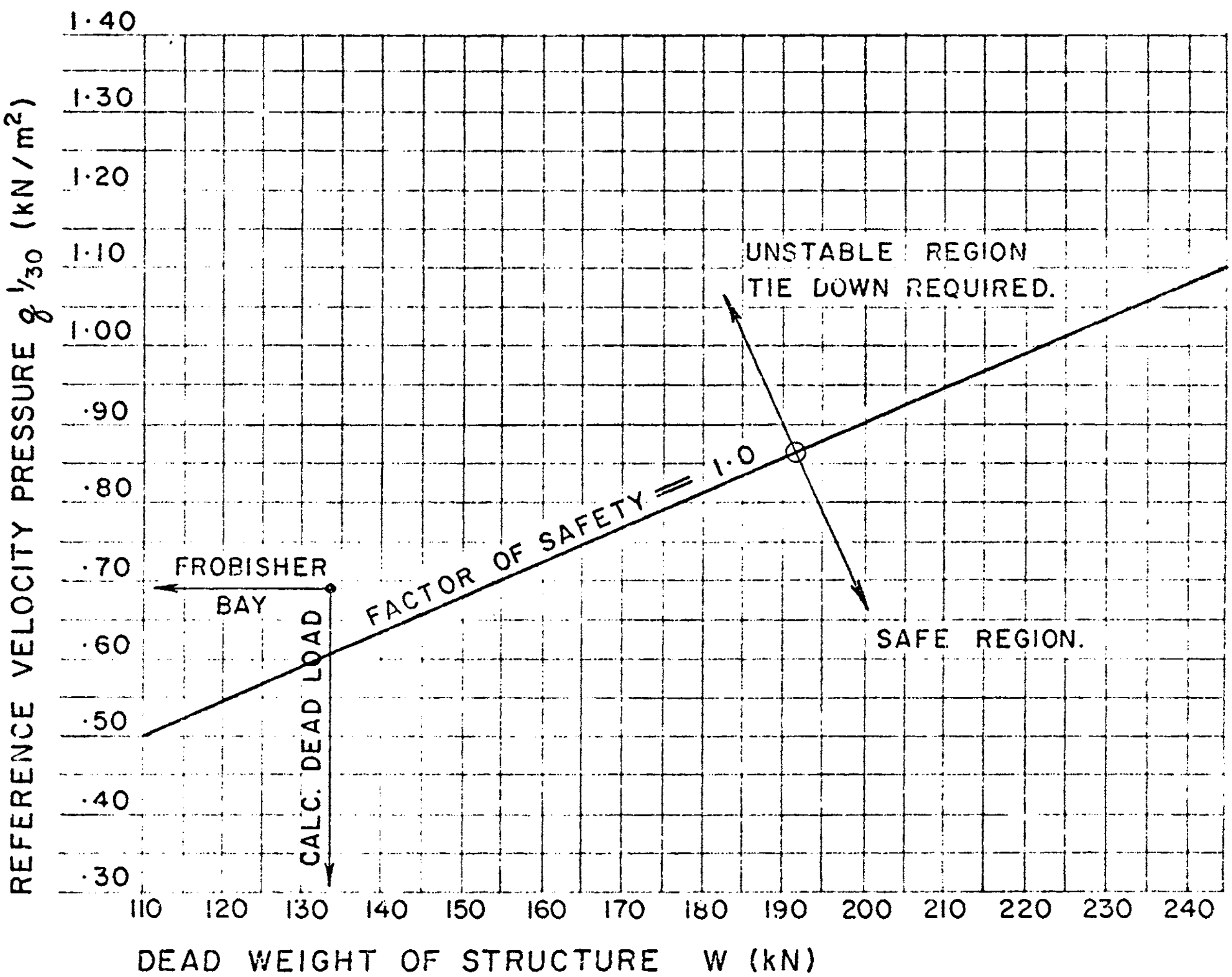


FIG. #3 — 7·31 x 9·14 SINGLE STOREY UNIT

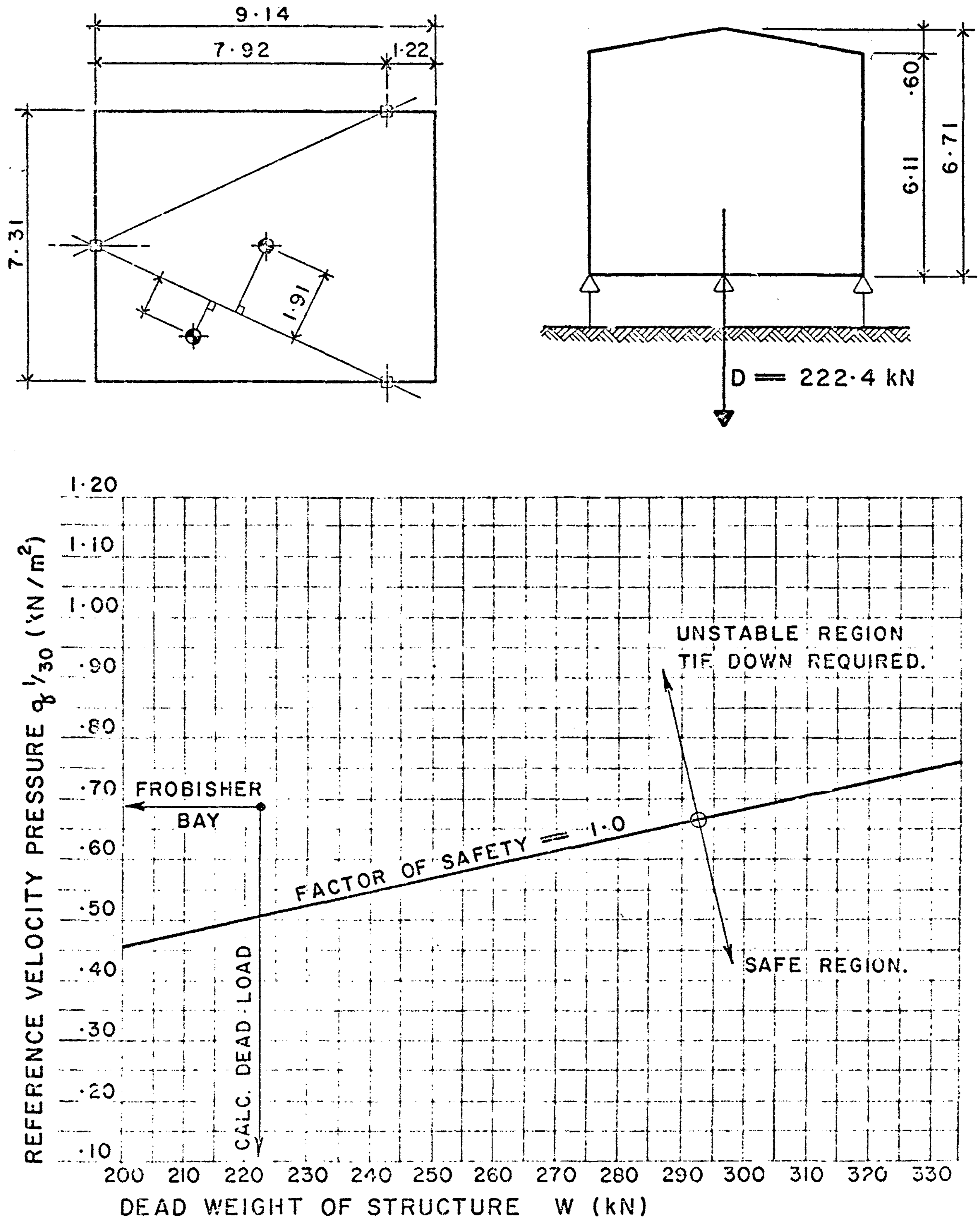


FIG. #4 —— 7·31 x 9·14 TWO STOREY UNIT

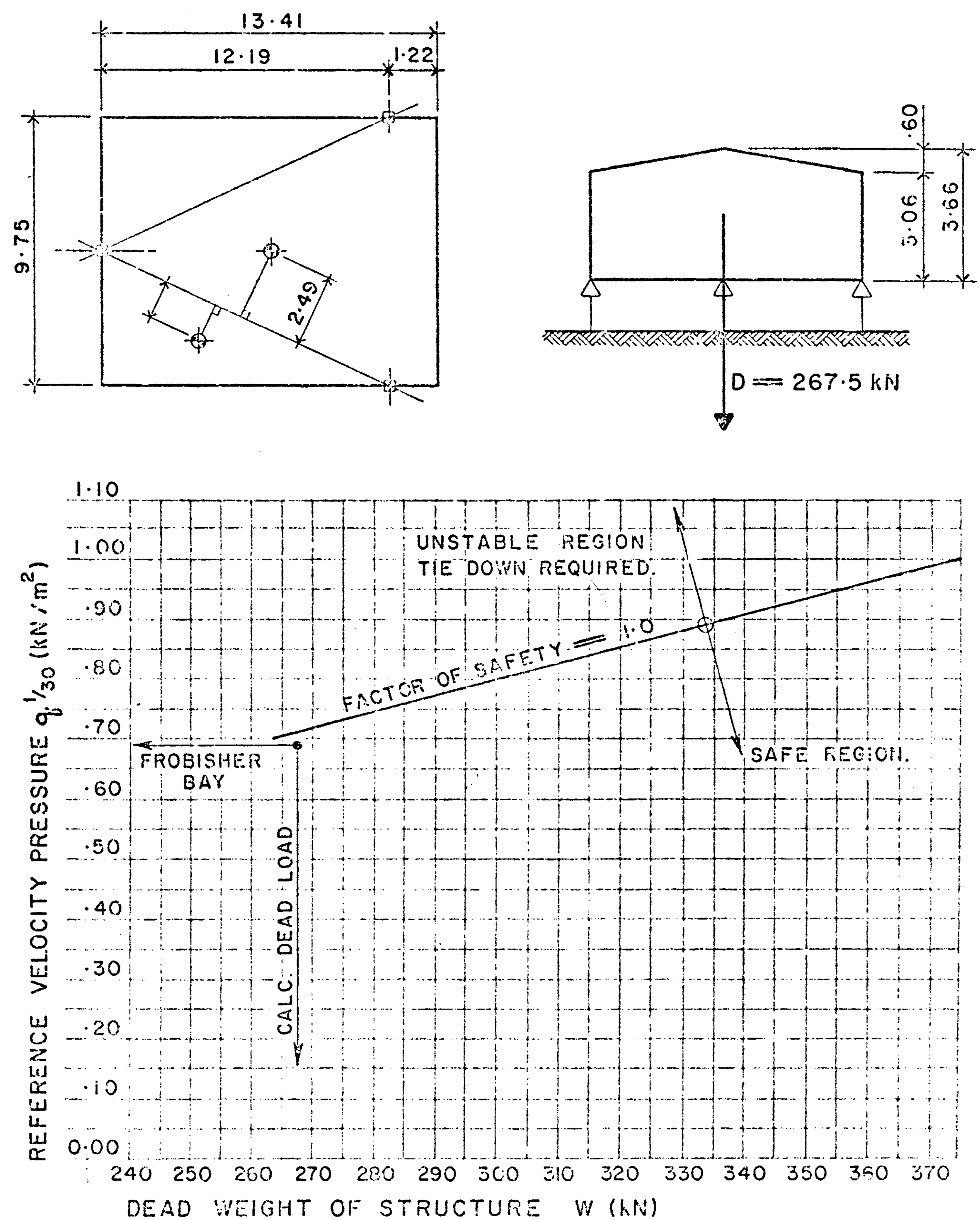


FIG. 5 — 9·75 x 13·41 SINGLE STOREY UNIT.