RESEARCH REPORT

Developing and Proof-Testing the "Prestressed Nebraska" Method for Improved Production of Baled Fibre Housing

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DEVELOPING AND PROOF-TESTING THE "PRESTRESSED NEBRASKA" METHOD FOR IMPROVED PRODUCTION OF BALED FIBRE HOUSING

By Fibrehouse Limited with
Scanada Consultants Limited

For Linda Chapman Architect

CMHC Project Officer: Don Fugler

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ABSTRACT

A method has been developed for prestressing stacked strawbale and other baled fibre building constructions, in which the prestressing is effected by means of the wire or plastic mesh which covers the exterior and interior surface of the strawbales. The mesh is normally required in any case to reinforce final stucco/gypsum renderings against shrinkage cracking. The prestressing method actually reduces the number of steps and components entailed in the hundred-year-old "Nebraska Strawbale" wall construction, the pioneer and still leading model. Prestressing tools were devised, using auto jacks. A structural test project, as well as field construction of a 1-1/2 storey studio, have been conducted as "proof of concept" demonstrations and exploration of the value of such prestressing in correcting or side-stepping the main problems and limitations of the Nebraska approach. That traditional system is a stressed skin/structural sandwich composite in which the final skin quality, including the tensile strength, is important if not indeed crucial. The testing proved that the one-step tensioning of the mesh from the top simultaneously and equally compresses the strawbales internally and together, greatly increasing the shear resistance as well as compression properties of the bales; the tensioning of the mesh acts with those properties to produce an adequate sandwich composite structure, to the point where the designer can avoid most or all dependency on the tensile qualities of any final renderings or coverings. The operation also accomplishes the final levelling of the walls, and can be used as well to produce pitched roof structure or arched or vaulted roof structures. The work also showed that the mesh preparation for prestressing bestows substantial construction stability and safety, eliminating the Nebraska system's tradition of using a forest of sapling dowels to attempt such stabilization prior to rendering. The new approach can also achieve plane surfaces that require much less stucco or plaster (or adobe, for that matter) and allows "shotcreting" rather than laborious hand stuccoing. The project, supported in part by the "HTIP" program of Canada Mortgage and Housing Corporation, has enabled Fibrehouse Limited to envisage a full-wall-length prestress rig, show how it can be used even for roof-ceiling envelope including curved arch or vaulted roofs, and apply for patent on 21 February 1996 under the title "Method and Apparatus for Prestressing Strawbale and Like Building Constructions".

EXECUTIVE SUMMARY

Background: The provision of affordable housing is increasingly limited by the supply of basic resources. Material resources are becoming less plentiful and less accessible, and material extraction is becoming more costly, energy consuming and polluting. Even wood frame construction, clearly the most successful system based on renewable fibre, is consuming forest resources at a questionably sustainable rate. Decades of innovations to improve sustainability, and "value-added" profitability, all have in common the production of "reconstituted" wood fibre composites, yielding more from less, but all at a price in terms of energy, money and pollution.

More than one hundred years ago, needing good houses quickly and lacking access to lumber, Nebraska pioneers conceived an alternative form of housing from an alternative cellulose fibre, a "waste" fibre in abundant supply and needing no refinement. Handsome examples of "Nebraska Strawbale" houses are still in use from those first days. The pioneers stacked bales of straw, then let them settle, rendered them on the outside with sand-lime stucco and on the inside with that or gypsum plaster, to form load bearing exterior walls. Their followers still do.

The Nebraska Strawbale system, for all its simplicity and ability to utilize the "wastes" of cereal grain agriculture — which is almost as broad as humankind — is not ready to produce housing affordably in volume, "by the millions, for the millions". The failings that have marred Nebraska Strawbale construction and all such prior art are any or all of the following:

- Much of the construction process is slow and marred by redundancies and wastes. Attempts to improve stability and safety during construction include the use of hundreds of saplings — or steel rebars, in some of today's versions — as vertical dowels pinning bale to bale, to little effect. Before the skins are applied, a settling period of 4-8 weeks is deemed necessary, with roof in place, to compress the bales sufficiently for the stucco/plaster work to commence on a stable base. This further interferes with construction flow and leaves the straw exposed to wind-driven rains.

- The shaky, uneven wall can take great amounts of stucco/plaster to form plane surfaces; it may not accept the impact of modern "shotcreting"; the hand-stuccoing is extremely laborious.

- The final structural properties rely very largely on the strength and stiffness of the skins, and on the straw's ability to transfer shear forces and to stabilize the skins against buckling under load. Stuccoed strawbale construction is in fact a stressed skin "structural sandwich" construction limited critically by the skin's structural properties.

- Nebraska strawbale construction and its derivatives can produce only the exterior walls, which constitute just a small fraction of a building. Limitations in strawbale shear and skin tensile properties make it unsuitable for forming roof-ceilings.

The Project: Fibrehouse Limited conceived a basic improvement to the Nebraska strawbale concept that bids fair to avoid or remove each of its drawbacks as just listed, and to entail less steps and components, transforming it into a more industrialized housing production process. This project, sponsored in part by CMHC's HTIP program, explores, develops and proof-of-concept tests Fibrehouse's "**Prestressed Nebraska**" concept for improved production of baled fibre housing of straw or other "waste" fibre.

In the Prestressed Nebraska concept, the "chicken wire" or other metal or plastic mesh (used in any case to reinforce the stucco, plaster or like skins against shrinkage cracking) is employed to compress the strawbale wall vertically, tensioning the mesh vertically with equal force. A top-mounted tool was conceived to pull up on the mesh on both sides of the wall at once, pushing down on the straw. This prestressing should ready the stacked strawbales to accept vertical loading without further deformation, greatly increase the shear of the strawbales to help develop both bending and racking resistance, and eliminate any structural reliance on the final skins, so that skin tensile quality is no longer of structural concern. The method should make the ready-to-prestress assembly stable and amenable to one-step adjustments to plane, and the quickly prestressed composite should accept "shotcreting" or like applications. The composite might be strong enough to form roof-ceiling structures.

The proof-of-concept project followed these steps: Loadings on one and two storey houses were calculated, strawbale stiffness and probable creep properties assessed, and the prestress forces determined accordingly to keep the mesh in tension and the skin material safely in compression, indefinitely. The proposed prestressing tool was fabricated as two working prototypes, Photos 1 & 2, and proof-tested under full load, Photos 3 & 4. A barn was rented and equipped for test panel fabrication and complete testing, Photos 5 - 9. Hydraulic and pneumatic test rigs were built (primarily by Internatural Canada for their Bioblock project under HTIP); electronic load cells and digital readouts were rented from Carleton University; the two parties together were able to afford a test set-up well beyond the grasp of either, singly. Strawbale wall panels were formed, roughly 3 ft. (one bale) long and 8 ft. high; thickness 18 in., i.e. the bale width. Load tests were devised to assess construction stability and safety on the unstuccoed panels without mesh, then with hand-tight mesh and finally fully prestressed mesh. The hand-tightened meshed panel was then stuccoed both sides and cured, now representing the normal Nebraska wall, more or less. Similarly, the prestressed mesh panel was stuccoed and cured to become a sample "Prestressed Nebraska" wall. The main tests followed: load/deflection tests simulating both vertical dead and live loads as well as horizontal "wind" loads (by means of an air bag), and combinations of same.

In the meantime, an opportunity was seized to build a 1-1/2 storey strawbale studio structure, and indeed to do it with untried Prestressed Nebraska approach (pressing the working prototype tools into service). Photos 10 - 16 show something of that project. Although well beyond the scope and budget of the HTIP project, and confused in work-study terms because of the many-hands "workshop" nature of the project, it added greatly to the findings of the lab development and test program.

Results and conclusions: **Figures 1 - 3** show the reassuring stability of the prestressed wall without any stucco or like skins; then the remarkable stiffness, strength and toughness of the complete Prestressed Nebraska wall - even after the stucco is cracked through, all over the tension side. Even the plain Nebraska wall - pre-cracked - showed little deformation, no set and no distress under vertical load of 14500 lbs - 4500 lbs per foot on the wall top - the absolute limit of the test rig and some 3.7 times the 2-storey design load. More critically, the bending testing of the prestressed panel, **Figure 3**, showed almost no effect when the stucco cracking point was exceeded, and the wall was still straight and sound - albeit creeping, probably in strawbale shear - at 153 psf, more than 7 times a hurricane design load.

The field project taught much, starting with the fact that the approach and even the first tools work as conceived, but going far to show the need for complete construction alignement and stabilization rigging incorporated with the new method, and the limitations of the spot-applied prestressers.

We conclude that advanced baled-fibre systems can be deployed efficiently and competitively in such a "Prestressed Nebraska" manner, using various fibre sources and rendering materials, to produce good housing in many regions. The test results are encouraging development of much more of the house than just the walls: the project has enabled Fibrehouse Limited to envisage a full-wall-length prestress rig, show how it can be used even for roof-ceiling envelope including curved arch or vaulted roofs, and apply for patent on 21 February 1996 under the title "Method and Apparatus for Prestressing Strawbale and Like Building Constructions". We are proceeding to put it to work.

RÉSUMÉ

Historique : Les ressources essentielles se raréfiant, il devient de plus en plus difficile de construire des logements abordables. Les ressources matérielles sont de moins en moins abondantes et accessibles, et l'extraction des matières premières est de plus en plus dispendieuse, énergivore et polluante. Même la construction à ossature de bois, qui est sans contredit le système reposant sur la matière fibreuse renouvelable le plus efficace, consomme nos ressources forestières à un rythme qui risque de mettre en péril leur durabilité. Des décennies d'innovations pour améliorer la durabilité et la rentabilité de la « valeur ajoutée » ont un trait commun : la production de composites à fibres de bois reconstitué permettant de fabriquer plus de matériaux avec moins de ressources; cependant, cette production est onéreuse, énergivore et polluante.

Il y a plus d'un siècle, alors que les maisons devaient être construites rapidement et que le bois de construction était inaccessible, les pionniers du Nebraska ont conçu une nouvelle forme de maison construite avec de la fibre cellulosique destinée au rebut qu'ils pouvaient trouver en abondance et utiliser sans transformation. On trouve encore de bons exemples des premières maisons en « bottes de paille du Nebraska ». Pour bâtir les murs extérieurs porteurs, les pionniers empilaient des bottes de paille, leur donnaient le temps de se tasser et enduisaient leur surface extérieure de stucco à base de sable et de chaux. Après quoi, ils enduisaient la surface intérieure de ce stucco ou de plâtre. Aujourd'hui, leurs successeurs emploient les mêmes méthodes.

Bien qu'il soit simple et utilise efficacement les « rebuts » provenant de la culture du grain pour l'élevage (aussi importante que la culture des céréales de consommation humaine), le système de construction en bottes de paille du Nebraska (Nebraska Strawbale) ne peut pas produire un gros volume de logements abordables, c'est-à-dire produire des millions de maisons pour des millions de particuliers. Parmi les inconvénients du système de construction en bottes de paille du Nebraska ou de tout autre système d'où il tire son origine, mentionnons les suivants :

- Une grande partie de ce procédé de construction est lente et vouée à l'échec en raison des redondances et du gaspillage. Cherchant à stabiliser davantage la structure et, ce faisant, la rendre plus sécuritaire, on a employé sans succès des centaines de gaules - ou barres d'armature en acier de fabrication contemporaine - comme goujons verticaux pour fixer les bottes de paille l'une à l'autre. Avant de pouvoir appliquer les revêtements, il faut mettre en place le toit et attendre de 4 à 8 semaines avant que les bottes de paille soient suffisamment tassées pour constituer une base solide au revêtement de stucco ou de plâtre. Cette période d'attente, au cours de laquelle la paille est exposée aux intempéries, nuit au bon déroulement de la construction.

- Le mur peu solide et irrégulier peut demander une énorme quantité de stucco ou de plâtre pour en faire une surface unie; il pourrait s'effondrer sous l'impact du béton injecté utilisé de nos jours; l'application manuelle du stucco est un travail extrêmement laborieux.

- Les propriétés structurales finales reposent grandement sur la solidité et la rigidité des revêtements et sur la capacité de la paille à transférer les forces de cisaillement et à stabiliser les revêtements pour les empêcher de gondoler sous la charge. La construction

en bottes de paille enduites de stucco est en fait une structure sandwich à revêtements porteurs grandement limitée par les propriétés structurales des revêtements.

- La construction en bottes de paille du Nebraska et ses dérivés peuvent produire uniquement des murs extérieurs, lesquels ne forment qu'une petite partie du bâtiment. Les limites des propriétés de traction des revêtements et de cisaillement des bottes de paille font en sorte que ce type de structure ne convient pas à la construction de toits en voûte.

Le projet : L'entreprise Fibrehouse Limited a amélioré le concept de la construction en bottes de paille du Nebraska et semblerait avoir éliminé les inconvénients susmentionnés ainsi que certaines étapes et composantes, transformant ainsi ce concept en procédé industriel de fabrication de maisons. Ce projet, parrainé en partie par le Programme d'encouragement à la technologie du bâtiment résidentiel (PETBR) offert par la SCHL, a permis d'explorer, de mettre au point et de valider le concept de la structure à éléments précontraints du Nebraska (**Prestressed Nebraska**) présenté par Fibrehouse Limited, en vue d'améliorer la construction de maisons avec des bottes de paille ou tout autre résidu fibreux.

Selon le concept de la structure à éléments précontraints du Nebraska, la broche à poulet ou tout autre treillis métallique ou plastique (utilisé pour renforcer le stucco, le plâtre ou les revêtements du genre afin de prévenir les fissures de retrait) est employé pour tasser verticalement les murs de bottes de paille en exerçant une traction verticale uniforme sur le treillis. Un dispositif monté a été conçu pour tirer vers le haut le treillis installé sur les deux côtés du mur tout en poussant la paille vers le bas. Cette force de précontrainte permet de préparer les bottes de paille à recevoir une charge verticale sans qu'elles ne se déforment, ce qui améliore grandement leur force de cisaillement et empêche leur fléchissement ou leur déformation. Ainsi, les revêtements ne servent plus d'éléments porteurs et les propriétés de traction des revêtements ne posent plus de problèmes de structure. Cette méthode devrait produire un ensemble précontraint stable qu'il suffirait de niveler, et le composite précontraint ne devrait pas se briser sous l'impact du béton injecté ou de toute autre application de ce genre. Le composite doit être assez solide pour former des toits en voûte.

L'essai de validation comprenait les étapes suivantes : Nous avons calculé les charges sur des maisons à une et à deux étages, évalué la rigidité des bottes de paille et leur résistance au fluage et déterminé les forces de précontrainte qui s'imposent pour garder indéfiniment le treillis tendu et les revêtements comprimés sans endommager ces derniers. Deux prototypes fonctionnels de l'outil de précontrainte proposé ont été fabriqués (photos 1 et 2) et testés sous une pleine charge (photos 3 et 4). Nous avons loué et aménagé une grange pour tester la fabrication des murs d'essai et effectuer d'autres essais complets (photos 5 à 9). Des bancs d'essai pneumatiques et hydrauliques ont été construits (principalement par l'entreprise Internatural Canada dans le cadre de leur projet Bioblock parrainé par le PETBR); nous avons loué des extensomètres électroniques et des lecteurs numériques de l'université Carleton; conjuguant leurs efforts, les deux partenaires du projet ont pu se payer un montage d'essai qu'ils n'auraient sûrement pas pu obtenir s'ils avaient dû l'acheter seuls. Nous avons formé avec des bottes de paille des panneaux muraux ayant une longueur de 3 pi (soit une botte), une hauteur de 8 pi et une épaisseur de 18 po (il s'agit de la largeur de la botte). Des essais de charge ont été conçus pour évaluer la stabilité et la sûreté de la structure des murs sans stucco ni treillis, puis avec du treillis fixé manuellement et, enfin, avec du treillis tendu à l'aide des outils de précontrainte. Pour fabriquer un mur qui ressemblait plus ou moins à la structure du Nebraska, nous avons appliqué du stucco sur les deux côtés du panneau auquel du treillis avait été fixé manuellement, puis nous l'avons laissé sécher. Dans le même ordre d'idées, pour fabriquer un mur qui ressemblait à la structure à éléments précontraints du Nebraska, nous avons appliqué du stucco au panneau à treillis précontraint, puis nous l'avons laissé sécher. Les essais les plus importants devaient suivre : il s'agissait d'essais de charge et de flexion simulant le poids propre et la surcharge (charges verticales) et la surcharge due au vent (charge horizontale calculée à l'aide d'un sac à air comprimé) et une combinaison des deux types de charges.

Entre-temps, nous avons profité de l'occasion pour construire avec des bottes de paille une habitation-studio d'un étage et demi. Pour ce faire, nous avons employé la méthode de la structure à éléments précontraints du Nebraska non éprouvée (en utilisant les outils des prototypes fonctionnels). Les photos 10 à 15 montrent certaines étapes de notre entreprise. Bien que cette dernière dépassait considérablement la portée et le budget du projet parrainé par le PETBR et que la terminologie de notre étude de travail engendrait parfois la confusion en raison de la main-d'oeuvre hétérogène participant au projet, notre entreprise a grandement enrichi les résultats du développement expérimental et du programme d'essai.

Résultats et conclusions : Les **figures 1 à 3** montrent la stabilité rassurante du mur précontraint, la rigidité, la solidité et la résistance remarquables de la structure à éléments précontraints du Nebraska malgré la fissuration complète du stucco sur le côté tendu. Même le mur Nebraska sans stucco ne présente aucune déformation importante, ni affaissement ni pli sous une charge verticale de 14 500 lb dont 4 500 lb par pied appliquée sur la partie supérieure du mur - soit la limite absolue du banc d'essai et environ 3,7 fois la charge admise pour une structure à deux étages. Fait encore plus important, l'essai de flexion du panneau précontraint, à la **Figure 3**, n'a eu presque aucun effet lorsque le point de fissuration du stucco a été dépassé, et le mur était encore droit et en bon état - malgré le fluage (sans doute attribuable au cisaillement des bottes de paille) causé par une charge de 153 livres par pied carré, soit 7 fois la charge prévue d'un ouragan.

Ce projet sur le terrain nous a beaucoup appris : du simple fait que la méthode de structure à éléments précontraints du Nebraska et même les premiers outils conçus fonctionnent comme prévu jusqu'à la nécessité d'intégrer à cette méthode des éléments complets d'alignement et de stabilisation. En outre, il nous a permis de cerner les limites des outils de précontrainte localisée.

Nous pouvons donc conclure que les systèmes de fibre en bottes évolués peuvent utiliser la structure à éléments précontraints du Nebraska de manière efficace et concurrentielle en employant diverses sources de fibres et du mortier pour enduit afin de construire des maisons solides dans de nombreuses régions. Les résultats des essais sont encourageants non seulement pour la construction de murs, mais encore pour la construction de maisons tout entières. Grâce à ce projet, l'entreprise Fibrehouse Limited a envisagé un banc d'essai de précontrainte sur toute la longueur d'un mur pour démontrer comment on peut s'en servir pour l'enveloppe des toits et des plafonds, y compris les toits en dôme ou les toits en voûte, et a soumis une demande de brevet le 21 février 1996 intitulée *Method and Apparatus for Prestressing Strawbale and Like Building Constructions* (méthode et dispositifs pour précontraindre des structures en bottes de paille ou tout autres structures analogues). Nous avons déjà entamé nos premières démarches.

CMHC SCHL

National Office
700 Montreal Road
Ottawa ON K1A 0P7
Telephone: (613) 748-2000

Bureau national
700 chemin de Montréal
Ottawa ON K1A 0P7
Téléphone : (613) 748-2000

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DEVELOPING AND PROOF-TESTING THE "PRESTRESSED NEBRASKA" METHOD FOR IMPROVED PRODUCTION OF BALED FIBRE HOUSING

Report for **CMHC-HTIP** by Fibrehouse Limited and Scanada Consultants Limited

Ottawa, 22 December 1995

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1. INTRODUCTION

Wherever people go, cereal grain agriculture goes with them. Cereal straw - tubular formed cellulose fibre offering the most strength from the least material - is created as a mostly wasted by-product in vast quantities: North America alone has over 35 million tonnes a year looking for use. The burning of rice straw wastes in California puts more pollutants into the air than all that state's thermal power plants together. Other similar waste fibre abounds: sugar cane bagasse, coconut coir, thatch palm, the grasses including bamboo... Excellent fibre, but mostly just a monumental disposal problem, not a blessing. Yet, wherever people go they need houses, and these "waste" fibres can be transformed into good houses.

In this project, supported in part by the Housing Technology Incentives Program of the Canada Mortgage and Housing Corporation, we explore, develop and "proof-of-concept" test what seems to be a most promising approach to transforming such organic fibre wastes into sound, affordable housing. Our approach is to take the time-tested "Nebraska strawbale" house construction and apply engineering and architectural thinking toward its transformation into a more industrialized housing production process.

2. BACKGROUND: THE NEBRASKA STRAWBALE WALL CONSTRUCTION

The Nebraska concept: In the Nebraska type of strawbale wall construction - the oldest, at about 100 years, and the simplest - the idea appeared to be to use the stacked bales themselves as the essential structure. They are placed in running bond and thoroughly pinned with slender dowels, and the wall is allowed to settle for a long period, with the roof in place, before the exterior and interior finishes are applied.

The proven Nebraska structure is not, however, a stacked block structure. At most, the strawbales take little more than the dead loads only, while the rigid skins - stucco or plaster, chicken wire reinforced - must accept all or most of any live loads. (Any imposed loads will be taken by the relatively high modulus skins with very little further deflection; such small further strains will scarcely be resisted by the straw.) In fact the still-yielding straw may finally adjust to take little of the dead loads either, after some decades have passed: the rigid skins prevent further settling overall; the straw "creep" manifests itself as stress relaxation; the dead loads are largely passed from the straw to the unyielding skins. As commonly built, the strawbale house wall is a stressed skin structure, of the structural sandwich type, in which the straw is simply the core which stabilizes the skins against buckling under load, takes the shear loads, and provides thermal insulation.

Misunderstood or not, the Nebraska method was not misconceived: it makes excellent use of material resources and clearly can produce durable, attractive and highly energy-efficient dwellings. The strawbale process is itself an outstanding old technology, producing bales with fibres oriented just right, as it happens, for stressed skin sandwich composites. The Nebraska wall is still the best model of sustainable natural fibre housing, but it retains drawbacks which keep such approaches from offering housing "by the millions, for the millions":

- A settling period of 4-8 weeks is deemed necessary for the roof and wall weight to compress the bales sufficiently for the mesh and stucco/plaster skins to be applied; even then, the lightly-loaded upper bales may scarcely have settled much.

- The long settling period leaves the straw exposed to wind-driven rains unless well tarpaulined. Building with dry fibre, and keeping it dry, is crucial.

- After such settling, the top plate must be relevelled. Settling will be uneven over windows and doors; the window sill elevations may need readjustment as well as the wall above.

- Despite onerous dowelling - which consumes hundreds of saplings - the wall remains shaky during construction and settling, until stabilized to some extent by the mesh and then completely by the cured skins. Tedious bracing and repetitious adjustments to plane are entailed. (And after the skins cure, all those saplings - or steel rebars in some of today's interpretations - have nothing whatever to do.)

- The uneven wall can take great amounts of stucco to form plane surfaces; the shaky core may not accept the impact of shotcreting; the hand stuccoing is extremely laborious.

- The wall construction is labour intensive overall; claims of economy tend to presuppose the use of cheap do-it-yourself labour; the number and efficiency of operations, the delay while settling occurs, and the hand rendering, are just not conducive to mass housing production.

- The thick walls may be top plated and window & door framed with excessive lumber, reducing the resource-efficiency advantages.

- The end product relies very largely, if somewhat indeterminately, on the initial and maintained quality of the skins and their mesh and/or fibre reinforcing.

3. A NEW CONCEPT: THE "PRESTRESSED NEBRASKA" APPROACH

This project is intended to develop substantial improvements to the Nebraska method of baled fibre housing, overcoming the cited drawbacks relating particularly to settling, rendering and the crucial dependence on the skins. The job here is to develop, prototype and try out a prestressing method - a core-compressing/mesh-tensioning approach - and show that it can use the existing mesh or chicken wire to these advantages:

- Create a smooth construction flow by compressing the wall immediately, eliminating any delays awaiting wall settlement.

- Streamline the levelling job by using the compression step to fine-level.

- Produce a much more stable and safe working base - and one which can accept shotcreting - by creating pre-tensioned skin planes on the stacked block structure early in the construction process.

- Compress the bales to the point where they may indefinitely carry at least the dead loads, easing the duties of the skins and the need for high quality skin materials.

- Pre-tension the skin reinforcing to the extent that the final skin material in the matrix will not be subjected to tension even under substantial live loads (wind, seismic) - further relaxing the structural quality requirement for the skin material.

- Simultaneously provide means of tie-down of roof to wall to foundation.

- Produce a pre-tensioned sandwich structure that remains stable even where the cementitious rendering is badly deteriorated or broken.

The new concept may be seen as essentially a bale pre-compression step by the strawbale construction enthusiasts. Since beginning this work, we have found that a few of the technical ones have indeed recognized that the Nebraska wall is largely a stressed skin wall insofar as live loads are concerned; none appear to have considered that stress-relaxation in the straw will tend to shift even the dead loads to the skins. Some have begun to explore pre-compression methods to eliminate the waiting for settlement. They generally employ extra rods vertically through the middle of the wall thickness; that's awkward and costly, and the rods' contribution to bending moment resistance is minimal in their position in the middle of the section.

On the other hand, engineers will tend to characterize the new approach as a pre-tensioning of the skin reinforcing steel, rather than primarily a pre-compressing of the straw core of the final structural sandwich. It is both: the prestressing action and its potential advantages depend upon exploiting the whole sandwich composite in a simple but novel way that we now explore and characterize.

4. PRESTRESSING REQUIREMENTS AND TOOL DESIGN

The technical knowledge base at the beginning of this project was scant, derived largely from the Delta projects as noted in the Chapman proposal to HTIP, 31 March 1995. The first project, the building of a Nebraska type strawbale studio, was observed by its architect Linda Chapman and independently by engineer Robert Platts of Scanada, resulting in close agreement on:

- the strengths, clear potentials and the drawbacks of the traditional Nebraska method as still practiced, as noted above;
- the need for a core-compressing/skin-tensioning step to avoid at least the main drawbacks and indeed improve the end product;
- and the idea that this could be effected using only the existing Nebraska wall components, particularly the light steel mesh or chicken wire that receives and reinforces the stucco.

Accordingly a second exploration was agreed to, an ad hoc venture in the Delta studio: set up a strawbale wall about 6 ft. long, instantly "settle" it by some means of tensioning the chicken wire, and see the effects. We used a worst case scenario of a sort, with poor quality bales, not dowelled, draped in the weakest chicken wire (22 gauge, 1 in. mesh). The first tool simply tore the wire. A second was devised to pull uniformly, and the wire was braced horizontally along the plane of the wall to forestall the "necking in" (an exaggerated Poisson effect) which leaves only the edge-zone wires trying to carry all the load. Prestressed to a vertical shortening of about 4 inches, the wall became remarkably stable even as a cantilever from the floor.

The crude tools were followed by three more concepts, on paper, all requiring balanced application to each side of the wall at once. The next step was to conceive a single top-mounted tool that could tension the mesh on both sides simultaneously. As illustrated later, the tool uses multifingered grapples to pull up on the mesh while it pushes down on the top plate. The idea encouraged Linda Chapman to propose this project to CMHC's HTIP office.

Loads

Dead loads and live loads, DL and LL, can be derived from a 1975 Scanada study for HUDAC - now CHBA - developing design criteria for house foundation systems for inclusion in the National Building Code. Developed for probable maximum loads on foundation walls under wood frame houses with roof trusses, where all roof loads may be assumed to be tributary to two exterior walls only, the results may be adapted conservatively to suggest design loads as impinging on the top of the first storey wall of strawbale structures. (The roof is larger and the loads are factored up accordingly because of the 1 ft. greater thickness of the strawbale wall compared to a 6 in. wood frame wall, assuming the interior space and the overhang remain the same. A 32 ft. wide house example is assumed. The strawbale wall DL itself is taken as 70 plf for the straw (30 lb. bale 3 ft. long, 7 bale high wall), plus 160 plf for 1 in. stucco skins, for a total of 230 plf.)

	1 - storey	2 - storey
Shingled roof incl. full insul, clg., about	140	140 plf DL
Second floor		62
Second storey wall		230
Total DL atop 1st storey wall	140	432 plf DL
Second floor LL		62 plf LL
Snow load	800	800
Total LL atop 1st storey wall	800	862 plf LL
Total DL+LL vertical, approx	940	1300 plf DL+LL

Wind loads: Assume a design load of 20 psf and a load factor of at least 2 - but not in combination with full LLs, especially snow load; these points will be considered in developing the test protocol.

Load factor: A doubling of the foregoing design loads - a load factor of 2 - is appropriate for proof testing and acceptance.

Prestressing Loads: Given the desirability of the straw taking at least all DLs, both its initial elasticity and its creep characteristics must be considered. The elasticity value is also needed in assessing the stressed skin sandwich characteristics that are the crux of all plastered strawbale systems. The recent Bou-Ali test results (ref. p.18 of this report), factored to represent an 18 in. wide bale rather than 24, suggests that a roof-ceiling DL of 140 plf would compress the stacked bale wall (no skins) about 0.5 in. That doesn't include the initial deformation due to its own weight, which must be considered when trying to assess instantaneous vs. plastic flow properties. The wall's 70 plf weight at the bottom acts as if a 35 plf top load were compressing a weightless wall, so that the Bou-Ali tests suggest a total initial deflection - following any loose surface "seating" - of 0.63 inches under a 175 plf load, or 0.81 psi on these 18 in. wide bales.

The stiffness of the bales seems to vary a great deal, depending on the baler (both machine and person) as much as the type of grain, number of twines, and density or degree of compaction - which in turn must depend on the bale's storage and handling history. Other testing, notably the recent work at TUNS, the Technical University of Nova Scotia, indicated rather low E values but that was to be expected: TUNS tested the bales as if they were independent blocks, more akin to concrete blocks. (But the work did measure what was called a Poisson effect, manifested in this case as the longitudinal bulging of the anisotropic fibre pack against the twines.) Bou-Ali recognized that the stacked bales are longitudinally constrained in any wall of significant length, which becomes true in any wall length once the mesh/skins are in play. That constraint - independent of, and exceeding, the binder twine effect - contributes strongly to the vertical stiffness and strength of the stacked bales. All assessments and prestressing trials here will have the vertical boundaries of the stacked bales constrained as if in a wall rather than a short panel, without interfering with vertical or out-of-plane horizontal displacements.

(The fibre orientation in a straw bale could have been expressly designed for structural sandwich purposes: the predominantly transverse or through-wall lie of the fibre, and its substantial length, packed overlap, and keying ability, allow it to stabilize the skins very well against buckle or wrinkle failure. The great transverse width of the bale also puts the skins so far apart that overall or Euler buckling is never of concern, and that width compensates as well for the lower thermal conductivity in the transverse, along-the-grain direction. The fibre orientation insures that the transverse dimension is fixed, in the stacked condition, even if the twines disappeared; that's also true longitudinally in a wall, as already noted: The twine strength and durability is probably only of concern for baling, storing, handling and construction, not for final wall performance in the immediate or long term.)

Probable Creep: Long-term plastic flow properties have been determined for various materials under allowable stress. As would be expected, the relative creep (creep deformation divided by initial deformation) for wood fibre is a consistent value if slippage and shear creep is kept out of the picture, and wood cellulose performance should be indicative of straw cellulose, applicable to bales once a certain amount of stacking looseness has been accommodated. Wood creep studies suggest that a 6 - 8 week period would see a relative creep of 30-50%, levelling off to become about 45-110% in 50 years. That would mean, in the Bou-Ali case, that a further straw deformation of about 0.5-1.0 in. would be expected under DLs only.

Almost all of that further deformation would be prevented by the rigid skins if they were applied and cured immediately, so that the straw would simply stress-relax toward a degree equivalent to the creep, passing most of the dead loads to the unyielding skins. However, if the skins were not applied until after some weeks of settlement, much or most of the creep would have taken place with the DL fully on the straw, and much less stress-relaxation would occur; much of the DL - but still essentially none of the LLs as they occur - would continue to be taken by the straw. Much more preferably, if the new method and tool were perfected to immediately precompress the stacked bales by an amount at least double the projected total DL deflection, including creep deflection - say 2.5-3.0 in. below the as-stacked elevation, in the case of bales of the Bou-Ali quality - then the bales would carry DLs and most or all LLs indefinitely, and would keep the mesh in tension with the skin material comfortably in compression.

Further, the Delta trials indicated that such mesh tensioning is sufficient to make the bales much more stable for construction purposes. The Bou-Ali test curves suggest the tool would have to exert a uniform pull of up to 667 lbs plf on the mesh, i.e. 333 lbs on the mesh on each side of the wall.

5. FABRICATION OF A PROTOTYPICAL PRESTRESSING TOOL

Tool Design: Starting with the over-the-top grapple concept of the proposal, a simplified tool was devised to use an auto jack to develop the prestressing force and displacement, **Photos 1 - 4.** All components were selected or designed capable of exerting up to the one ton force as derived earlier, with a load factor of about 1.1; the grapples spread the load over a 1-metre length of wall, engaging the mesh on both sides at once. While the tool would best be made of steel, the Bedford Crescent lab is equipped to work with wood. Two working prototypes - mock-ups, more like - were made from oak as shown. (At least two are needed in the field to prestress a length of wall at a time, leapfrogging along.) The cable lifts are underslung as shown to help improve stability in set-up and loading.

The Rube Goldberg test set-up of **Photos 3 & 4** proved that the light rig could just exert the required 2000 lb. force. As will be noted later, the tool concept and execution is being superceded by a couple of generations, but the mock-ups did the lab and field jobs for this pioneer project.

6. STRUCTURAL TESTING

General: All wall construction and testing were carried out in the Chelsea barn specially rigged for such work job by Internatural Canada with Scanada engineers. Also under HTIP support, Internatural was concurrently proceeding with R&D on its "Bioblock/Biocrete" system, somewhat akin to the Nebraska approach but primarily using shredded wood wastes and developing a unique "blockmaker" baler to accommodate such fibre stock. Neither project could afford the shop and structural test rig; sharing the engineering, construction and rental charges allowed both to proceed.

The tests characterize the prestressing process and the resulting product in terms of meeting the intent and requirements given above. The scope and budget did not include research on straw bale and/or skin material properties; these have been established by others. All the bales appeared to be well formed, sound and dry. A 1-in-3 sampling was weighed and measured before the testing began.

The stacked straw "core": Test walls were built as "panels" about 3 ft. (one bale) in length and about 8 ft. high, **Photo 5**. One stacked panel was left aside, untested, to observe settling. (Another was left to settle for 10 days prior to its use in the prestressed mode, to help differentiate the prestressing compression from the settlement.) As a comparative indicator of sorts on construction stability, the stacked walls' resistances to overturning and mid-point bending were tested as described under Results.

The straw core with mesh: 22 gauge, 1 in. "chicken wire" mesh was draped over two test panels and secured to the floor plates (representing sill plates anchored to the floor slab/foundation). The mesh was well braced horizontally in its plane to act as it would in a full, tied-in-plane installation, i.e. constrained against necking in and therefore able to take the vertical tensioning uniformly and fully. As can be seen in **Photos 5 & 6**, the bracing of the wire also served to constrain the strawbale ends in order to represent a full wall in terms of prestressing and other load resistance characteristics.

In this first case the mesh was simply hand tightened vertically and horizontally, with a pull of roughly 30 pounds at one foot spacing around the perimeter of the mesh, roughly representing the initial application and then the tying of roll to roll in a normal Nebraska application. While some Nebraska system practitioners suggest transversely tying together the two mesh planes with wire ties pushed through the straw, we decided to test the simplest no-ties composite where the straw alone must tie into and transversely stabilize the final stucco skins. Before stuccoing, the wall stability was tested again.

The compressed core/tensioned mesh wall ready for rendering: The second strawbale wall - already presettled 1.0 inches - was compressed under a force of about 600 lbs. per foot, a total of about 1800 lbs., by pulling up on the mesh and pushing down on the top plate with the prototype prestressing tool, **Photos 2 & 7**. The stability of the greatly stiffened wall was measured again, as a comparative indicator of construction stability during the operations leading up to the application of the structural skins.

The Nebraska wall: Stepping back a little, the first wall panel was left as built, with the wire mesh just hand-tight, Nebraska style, while the stucco skins were applied and cured: **Photo 8**. The stucco was applied about 3/4+ in. thick, using a moderately weak lime-cement premix ("Techmix, meeting ASTM Type N, rated at 6.6 kPa at 7 days, 8.2 at 28). Stuccoing began 19-11-95, testing on 30-11-95; the faces were kept damp for the first few days and probably never dipped below zero celsius in the first 7 days. The faces were formed about 39.4 in. wide to protrude a little past the bale ends, and the vertical edges thickened a little, to compensate for the weakening effect of the edge discontinuity relative to a continuous wall. The panel was tested to establish load/deflection characteristics under vertical dead loads and live loads (DLv and LLv) up to the one-and-two storey design loads as given earlier, then doubled; then the "wind" loads LLh were applied by airbag while DL was maintained, increasing the wind load to explore the point and mode of failure:

- DLv + LLv (snow & floor LL)
- DLv + LLh(wind)
- DLv + increasing LLh to point of tensile failure (initial cracking) of stucco skin
- Assess remaining resistance to loads with skin initially and then badly cracked.

The new product - the Prestressed Nebraska wall: Using the second strawbale assembly in its prestressed state, stucco was applied and cured much as above, but better planarity of straw and mesh allowed the skins to be controlled to an average thickness of 3/4- inch. Here the faces were formed 37 in. wide, again protruding past the bales (shorter in this panel) and thickened as above to compensate for edge discontinuity. The cured final product, **Photo 9**, was tested fully as above.

7. TEST RESULTS

The bales: The wheat straw bales were firm and well formed, with widths consistently 18.5 in. and depths 13.95 - 14.0 in. Lengths varied from 32 to 37 inches, however, and weights from 35 to 42 lbs fairly commensurate with length. The average bale measured 18.5x34.5x14.0 in. and weighed 36 lbs. - density 7.0 pcf in what was clearly a well air-dried state (moisture not measured). The set-aside bales in the settling trial had not been weighed or measured.

The settling trials: The 7-bale stack settled 1.17 inches over a 2 week period, from an initial height of 96.25 in. to a final 95.08 in. The values may not mean much: they seemed to depend somewhat on the time of day/temperature of the close-by wood stove, and the set-aside bales must have been pre-settled (perhaps from a low position in the barn loft) since the panel height was unusually short.

Hand tensioning and full prestressing: The effect of adding the wire mesh, hand taut and well secured at the base plate, is clear. First, the 7 bale stack was reduced by 1 in. in height from its initial 97.75 in.; the stiffening effects are noted below. In the case of the second panel, already settled 1-in., waiting to try to isolate the Nebraska settling effect from the further effect of prestressing, the mesh application itself appeared to have little further effect but the prestressing force of about 600 - 700 lbs/ft compressed the wall an additional 2 inches. The mesh was pulled up about the same amount, to extend about 4 in. above the top plate, **Photo 7**; the excess is clearly ready to form a very strong tie-down link for roof structure. (In **Photo 9**, the shortening due to prestressing can be seen in the foreground panel against the hand-taut panel behind it. The edge pieces and poly helped in stuccoing.

Construction stability before stuccoing: **Figures 1 & 2** show the stacked bale resistance to top overturning and mid-height bending loads, respectively. The stiffening effect: whereas a 4-5 lb force overturns the 3 ft. long wall without the mesh, a 25 lb. force pushes it only 7.5 in. off plumb with the light chicken wire in its Nebraska wall state. At that load, it appeared that the stack was beginning to deform primarily in sliding shear between the bales. A little of that was observed in the mid-height bending tests as well, without and with the mesh in this mode. The stack was readily re-plumbed for stuccoing.

Turning to the prestressed panel, the stiffening and strengthening effects are dramatic, as seen in the load/deflection curves: A 40 lb. force pushes the prestressed, cantilevered stack just 1.75 in. off plumb; an 80 lb force at mid height bends the top-restrained stack about 0.3 in. only. The stack behaved elastically with no shear slippage and no set. (All forces were applied through a 1 ft. long horizontal bar centred on the panel face, and deflections measured on the bar.)

Tests of the completed walls: Figure 3 records the load/ deflection performance of the Nebraska panel whole, then in its test cracked state, and finally the Prestressed Nebraska wall. First, however, vertical testing was done on the strengthened test rig, for which no curve was drawn because very little deformation was detectable.

1) **Test 1, Nebraska, vertical loading** to 1-storey design load, 2820 lbs., then doubled; then to 2-storey design, then doubled -

- **at 8832 lbs - 2944 plf - defl. 1 mm** in height; no other deformation; no set

2) **Test 2, Nebraska, "wind" load**, with 1-storey dead load (140 plf), Figure 3:

- stucco cracked across tension skin just under **80 psf (3.83 kPa)**
- load taken to 80 psf - 4 x design wind load - held for 10 min.,**no creep**

The crack appeared to be due to flexure of the stucco as the straw deformed in compression and "punch" shear at the top restraint; the stucco would also be under considerable shear and some tension at the crack zone. The panel remained stable, inviting further exploration of the crack effect under vertical load.

3) **Test 3, Nebraska pre-cracked, vertical** loading....
Trying for failure, to limit of strengthened test rig:

- **at 14500 lbs - 4500 plf - defl. 3mm** in height; no other deformation; no set at 3.7 times the 2-storey design load...

The crack seemed to have no effect: the broken stucco was still fully restrained against buckling. The test was stopped because the rig's top yoke beams began to creak and groan.

4) **Test 4, Prestressed Nebraska, wind** to failure; worst case with no vertical load, **Figure 3:** stiffening and strengthening effects are clear.

- **Tension stucco cracks at about 6.5 kPa** Little if any change in slope, performance...

Again, the first and worst crack was near the top (14 in. down), where the stucco was clearly bent as the straw deformed against the top restraint, and a little shear offset was apparent. But other cracks appeared almost immediately, at the same load or little more; they also ran clear across, 28, 55 & 77 in. from the top, and looked more like tension cracks with no shear offset. Loading continued:

- **Creep became apparent at about 7.5 kPa** (about 153 psf) ...over 7 times the design load.

The prestressed sandwich is behaving much like a floor structure, not just a vastly overstrong wall: the system development can and should be extended into pitched and arched roof-ceiling forms, to encompass much more of the house envelope.

8. FIELD TRIALS

The project was to include rather limited field trials of the tool and method; within the budget, it was hoped that much could be learned during the construction of the test wall panels themselves, and perhaps by constructing a further trial wall section at least to the point ready for rendering. The protocol would be to focus observations on the usability and improvability of the tool, and perhaps little more, all within the budget constraints.

This work would have accompanied or followed the test preparations, then proceeding to the trial wall assembly without stuccoing. An opportunity intervened before any of that, however: A Gatineau area builder, Yves Dorval, approached Linda Chapman seeking architectural and engineering help in building a 1-1/2 storey garage with studio over. The wood prototypes of the prestressing tool were rushed to completion, as pictured earlier. Recognizing that the Nebraska system itself was more than able to handle the low load and usage requirements, and that Prestressed Nebraska can be nothing but stronger, the project was undertaken without awaiting the physical testing. It stands as a greatly expanded field trial for this HTIP project.

Photos 10 - 15 show much of the building project. An ample supply of barn frame timbers led the builder to chose a hybrid design, in which the second floor is supported on post and beam, independently of any walls, while the 13 ft high Prestressed Nebraska strawbale walls support the roof and roof loads (using half-storey roof trusses to yield studio space) and resist wind and other racking loads.

9. RESULTS AND CONCLUSIONS

The field trials, together with the test lab findings, presented no great technical surprises or difficulties but surely packed in some lessons.

The prestressing method and crude tools worked fairly well in themselves, although the concentration of the tools within a short length of wall tended to overload tools and mesh, and the leapfrogging of tool over tool proved slow. Many of the snags of the Nebraska method remained stubbornly obstructive, just as listed in the background section.

On the one hand, the waiting for settling was eliminated, planarity improved, construction safety assured, the fine levelling facilitated and the structure clearly solidified, all by the prestressing step together with the light lateral-girder top plate, **Photos 10 & 11.** On the other hand, however, the many steps before that and the one huge step after - stuccoing - still begged for elimination or simplification. The project was bedeviled with light, ill-formed, sleazy bales, **Photo 12**. The dowels (saplings or steel) do not work well even for their temporary job of fixing the bales against transverse slip, because they slip easily in that direction, between the transversely layered straws. Much time was lost in plumbing and then re-plumbing the high walls.

The prestressing pulled the structure together dramatically into stable plates, but could not make smooth vertical planes out of the unevenly-thick bales, **Photo 13**. The "workshop" nature of the project confused any sense of work-study, in that the hands were many and most were on the steep slope of the learning curve. And the builder could not get a reasonable bid on shotcreting and so elected to stucco the uneven bales by hand. But the strawbale building - perhaps the first to use 1-1/2 storey bearing walls uninterrupted by floor structure - shaped up nicely, **Photos 14 & 15**.

Lessons were learned, conclusions reached and solutions conceived. On the basis of the concept and this project, Fibrehouse Limited is founded to promote efficient "Prestressed Nebraska" housing construction much as now outlined:

A: Off-site:

- Good balers and good bales are a must.
  (Dedicated baling, and including half bales too?)

- Good, modular-dimensioned architecture.

- Top plates (along with trusses, window & door subassemblies, perhaps partition framing...) should best be prefabbed for each house plan?

B: On-site

(Here presuming slab-on-grade; house plan templated by anchored sill plates]

1. We are working up a corner post & cable erection jig for the whole.
   - cable and stays at certain elevation
   - with a moveable, light plumb jig on slab

2. One pass stacking/plumbing is crucial to efficiency.
   - good bales, no dowelling
   - cable-stayed as above, out of way
   - windows & doors jigged in, cable-stayed
   - all work from benches, <u>not</u> on bale wall
   - set the through-corner ties as courses progress?
   - set flakes on flat over windows & doors for extra compressibility

3. "Freeze" the rough structure
   - place and join top wall plate all 'round
   - rough level with flakes under plate
   - place and anchor mesh in new fashion as now being developed, with cable and stays still in place
   - pin mesh through bales to hold at corners?
   - claw-tie all mesh; pull down high points of wall
   - relax the cables and complete the mesh/claw ties at wall corners
   - all "frozen" - pull the cables and stays from under the mesh.

4. Prestress and fine-level
   - we have conceived a one step, whole wall prestress rig that uses the mesh as now, "instantly" and with uniform loading of straw and mesh; uses pneumatic, hydraulic or mechanical options to fit any region.
   - and then fine-levels the whole.

5. Place and tie down roof structure (or floor platform, if 2-storey)
   - flaps of mesh are ready to do this securely.

6. Stucco exterior (shotcrete)

7. Place partition frames

8. Rough wiring

9. Interior finish (gypsum plaster is adequate...)

We conclude that advanced baled-fibre systems can be deployed efficiently and competitively in such a "Prestressed Nebraska" manner, using various fibre sources and rendering materials, to produce good housing in many regions. The test results encourage development of much more of the house than just the walls: the project has enabled Fibrehouse Limited to envisage a full-wall-length prestress rig, show how it can be used even for roof-ceiling envelope including curved arch or vaulted roofs, and apply for patent on 21 February 1996 under the title "Method and Apparatus for Prestressing Strawbale and Like Building Constructions.

Current Reference Material

The scanty knowledge base was first filled in a little by review of several works. Helpful material was found in: The Strawbale House Book, Steen et al, 1995 - the only one in which some professionals - an architect and an engineer independently - are noted to be recognizing the fact and some of the meaning of the stressed skin composite action - while the authors may not be; Thermal and mechanical properties of straw bales as they relate to a straw house, Watts et al, TUNS, 1995 - which is useful too but the engineers appear to show no recognition of that crucial composite action; the quarterly newsletter The Last Straw, and the 1995 book Build It with Bales, both by Myhrman et al; and the bale wall testing by Bou-Ali in his Civil Engineering master's thesis at the University of Arizona, 1993: Straw bales and straw bale wall systems. Structural sandwich engineering works were also reviewed, and studies on plastic flow (creep) and stress-relaxation. Finally, the proceedings of the "Straw into Gold" symposium, Winnipeg, 23-26 October 1995, proved very useful in outlining the resource breadth and depth of "waste" cereal straw.

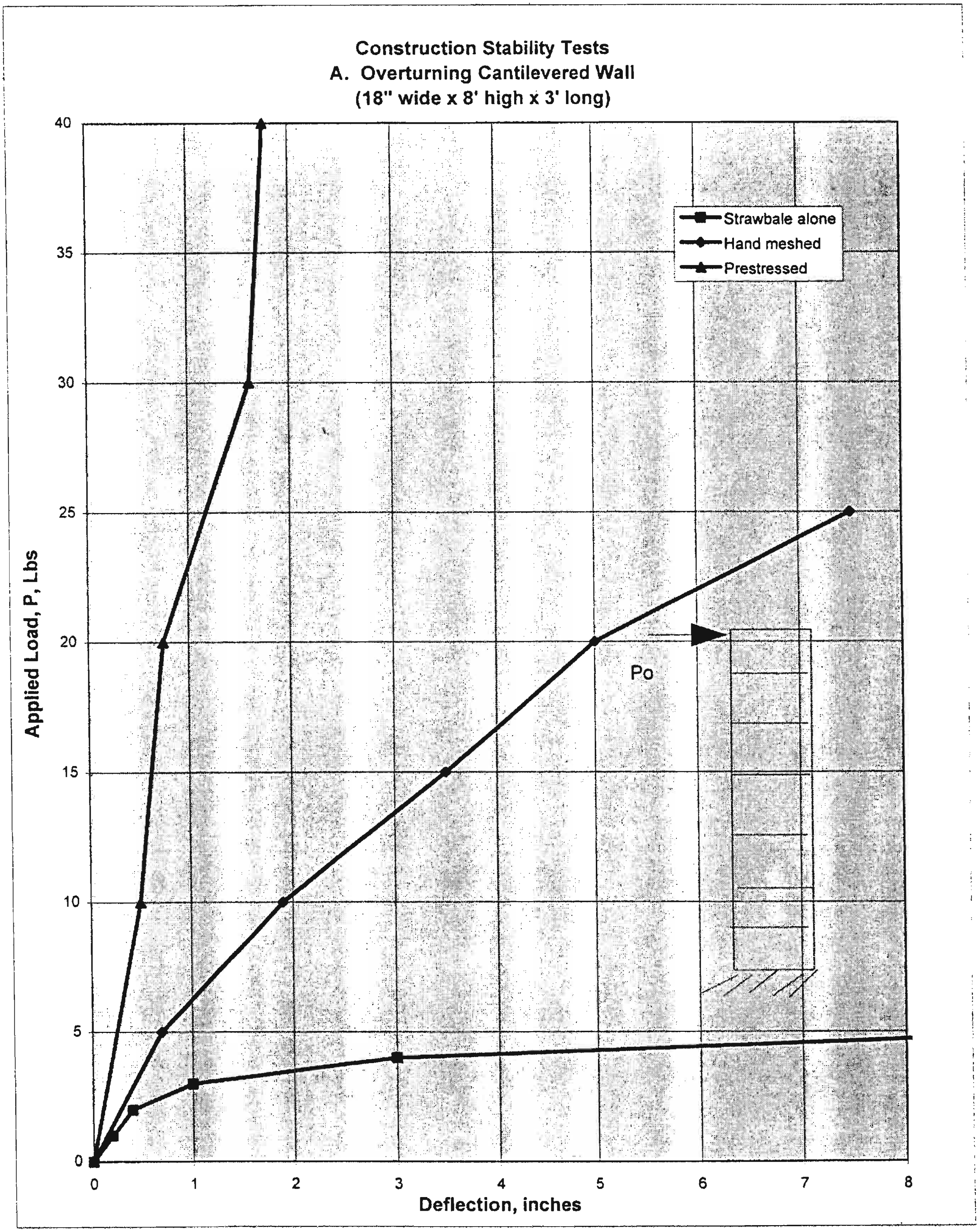
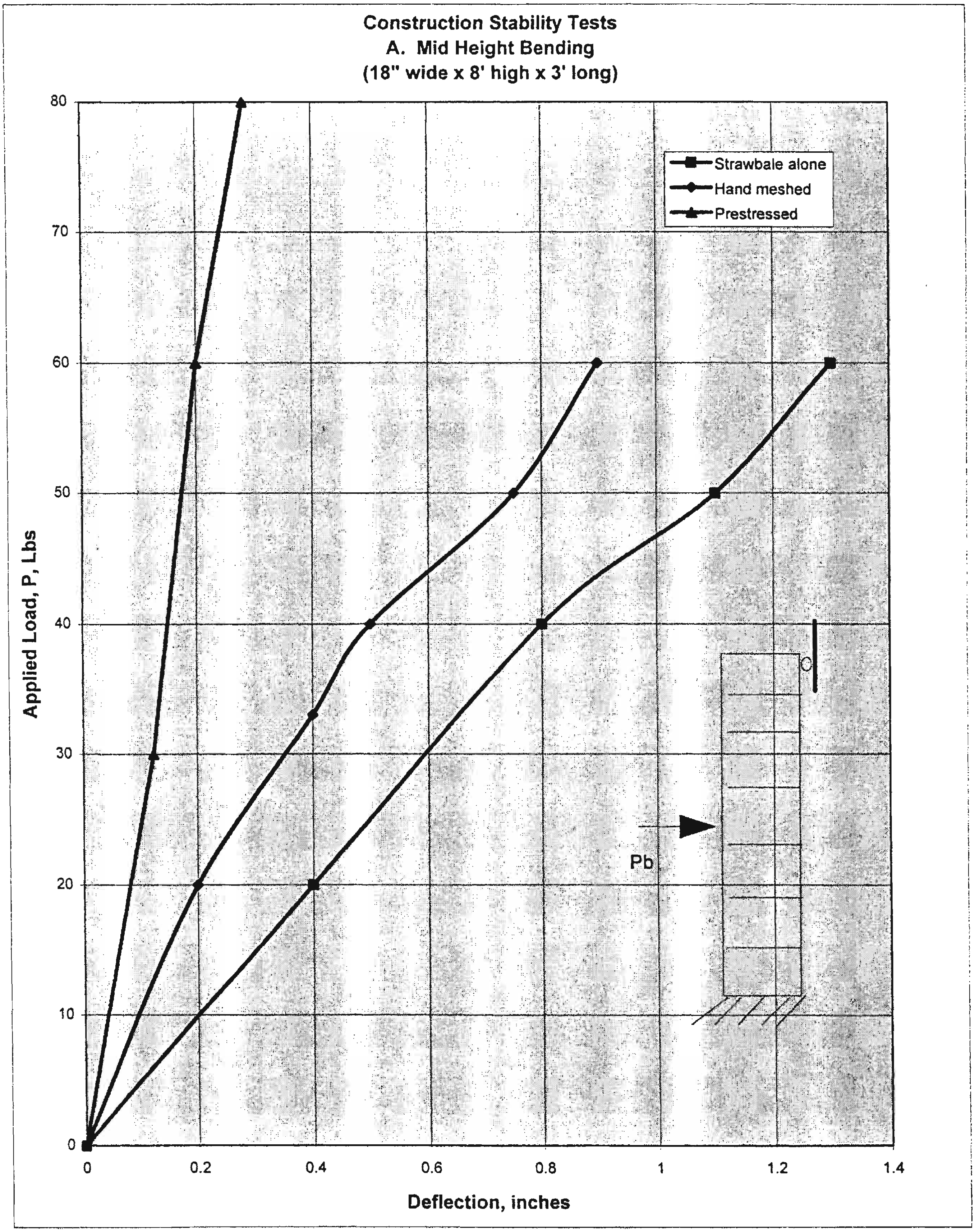
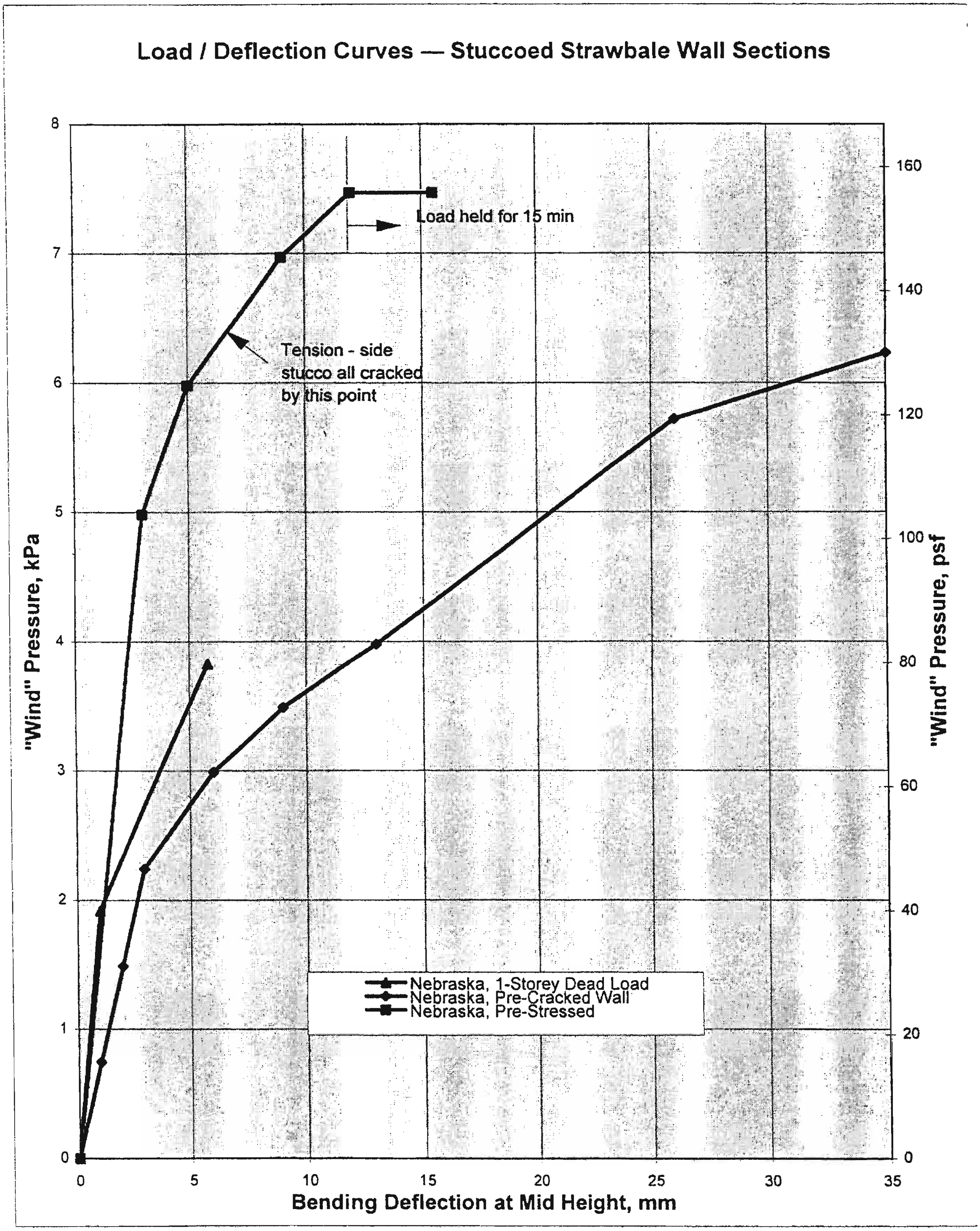

Construction Stability Tests
A. Overturning Cantilevered Wall
(18" wide x 8' high x 3' long)
Applied Load, P, Lbs
Deflection, inches
Strawbale alone
Hand meshed
Prestressed
Po
0
5
10
15
20
25
30
35
40
0
1
2
3
4
5
6
7
8

Figure 1



Construction Stability Tests
A. Mid Height Bending
(18" wide x 8' high x 3' long)
80
70
60
50
40
30
20
10
0
Applied Load, P, Lbs
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Deflection, inches
Strawbale alone
Hand meshed
Prestressed
Pb

Figure 2



Load / Deflection Curves — Stuccoed Strawbale Wall Sections
Load held for 15 min
Tension - side stucco all cracked by this point
Nebraska, 1-Storey Dead Load
Nebraska, Pre-Cracked Wall
Nebraska, Pre-Stressed
"Wind" Pressure, kPa
"Wind" Pressure, psf
Bending Deflection at Mid Height, mm

Figure 3

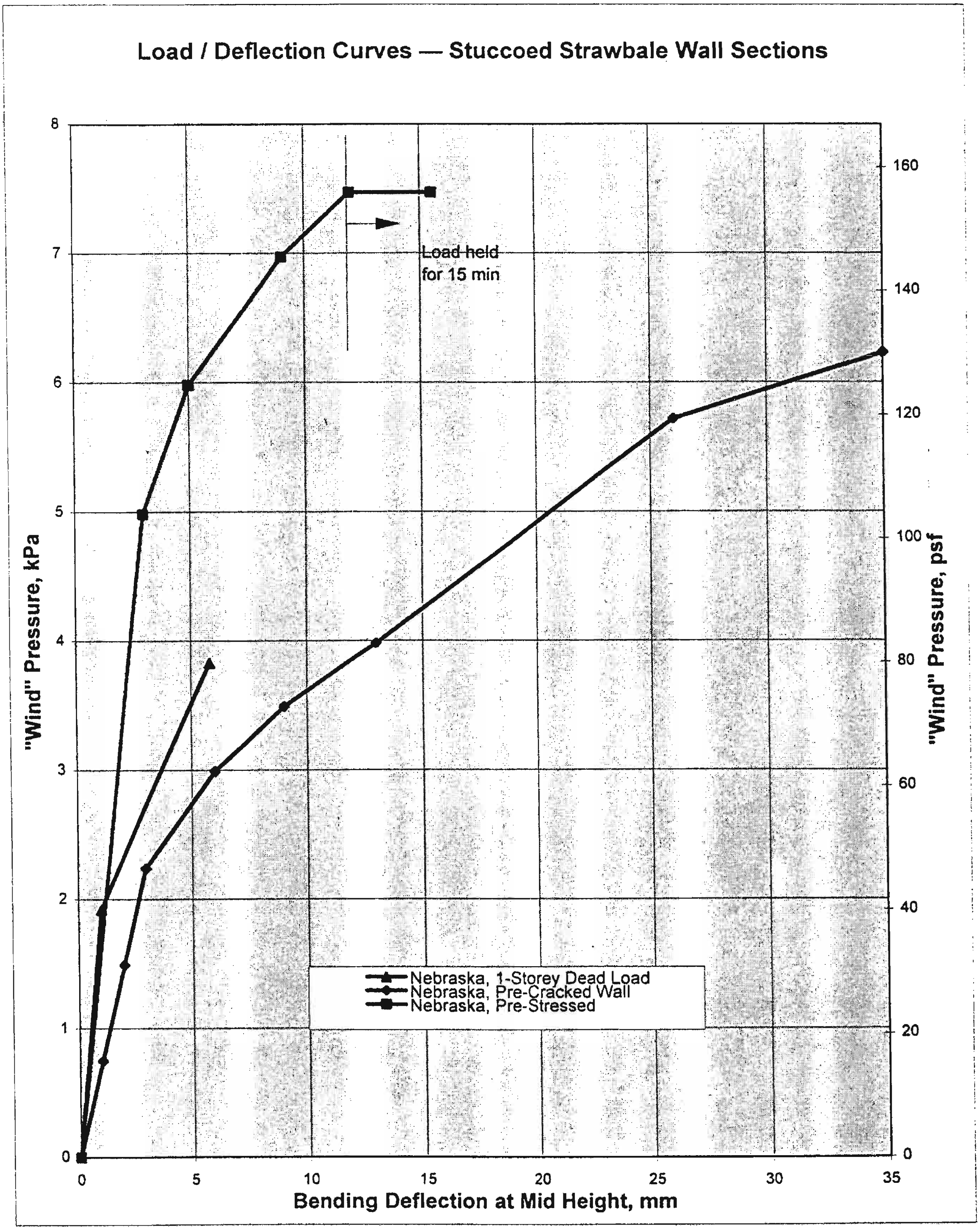

Load / Deflection Curves — Stuccoed Strawbale Wall Sections
Load held for 15 min
Nebraska, 1-Storey Dead Load
Nebraska, Pre-Cracked Wall
Nebraska, Pre-Stressed
"Wind" Pressure, kPa
"Wind" Pressure, psf
Bending Deflection at Mid Height, mm
0
1
2
3
4
5
6
7
8
20
40
60
80
100
120
140
160
0
5
10
15
20
25
30
35

Figure 3

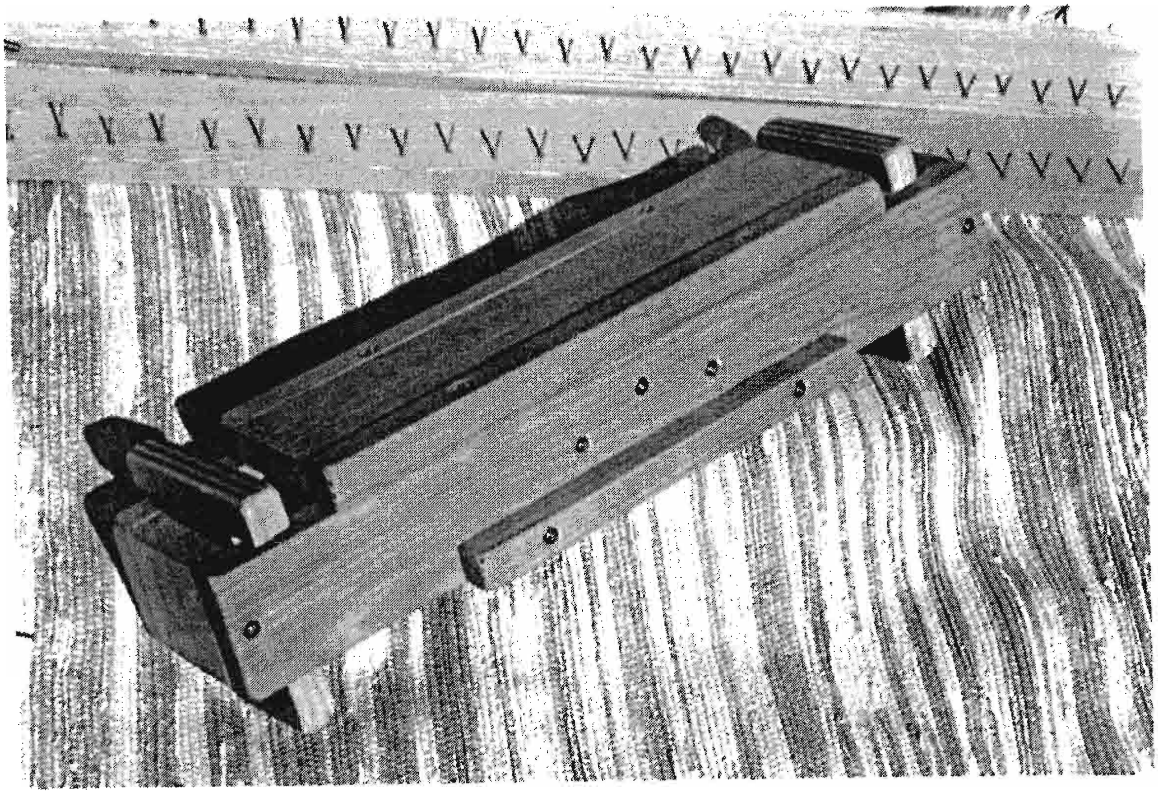


Photo No. 1

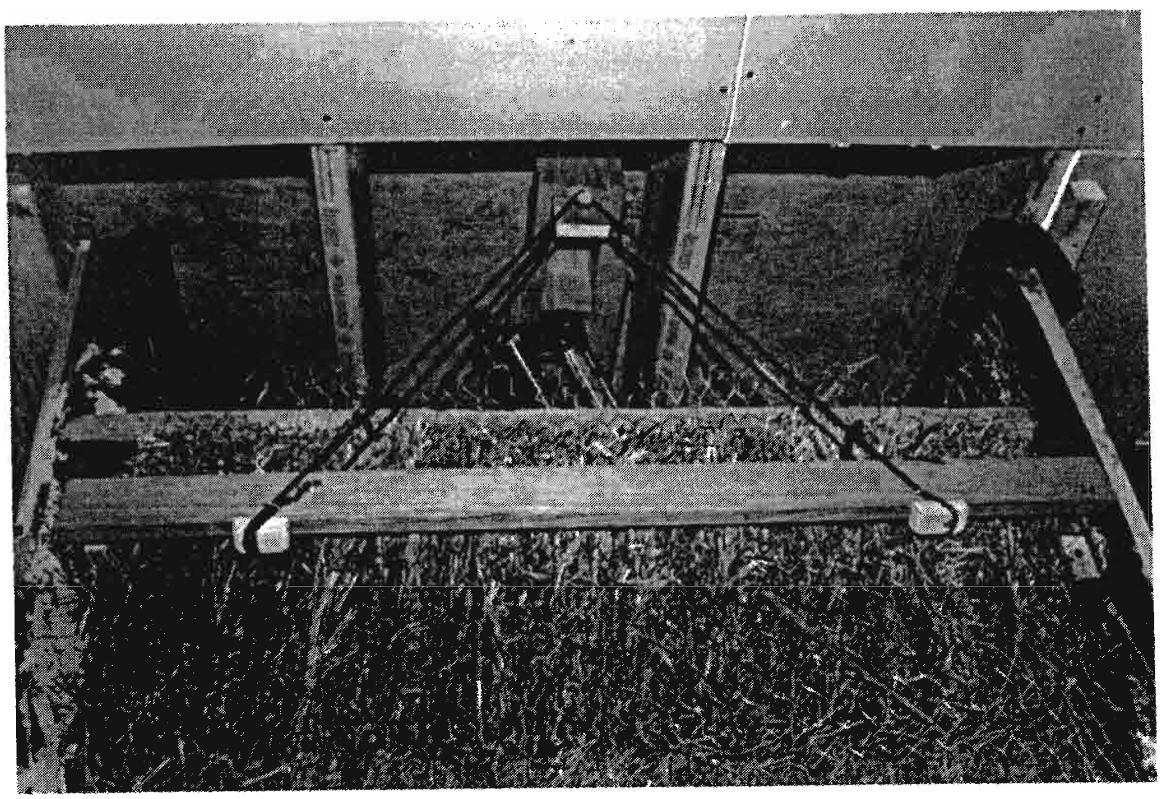
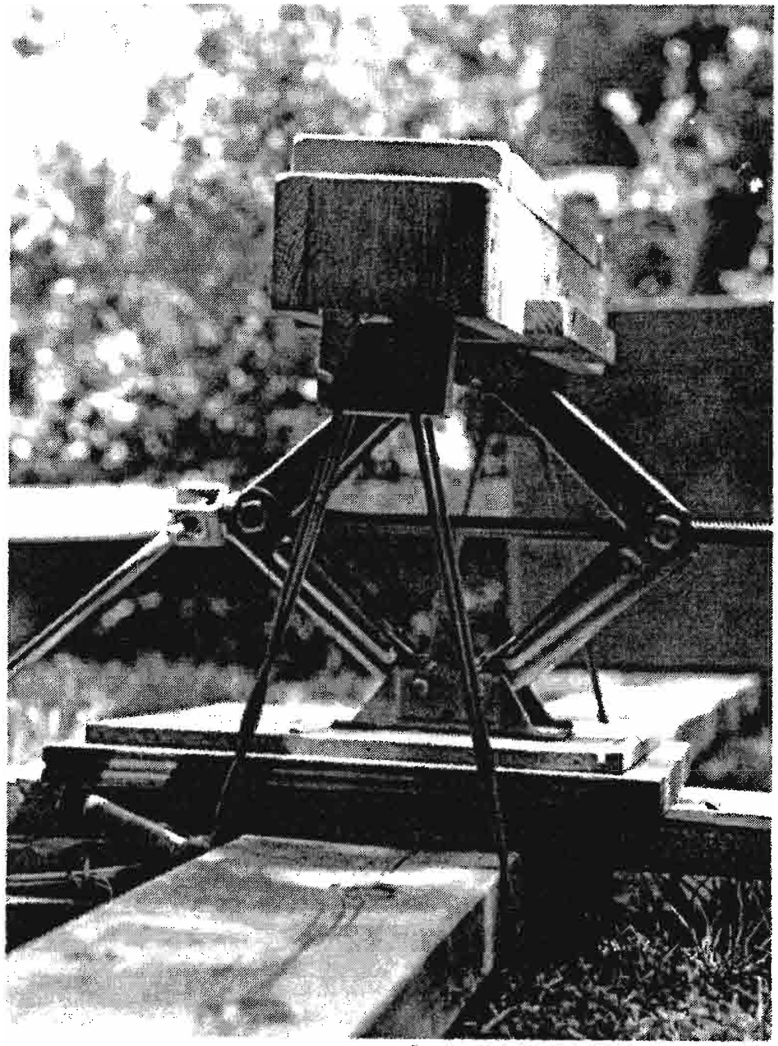


Photo No. 2

Photo No. 3



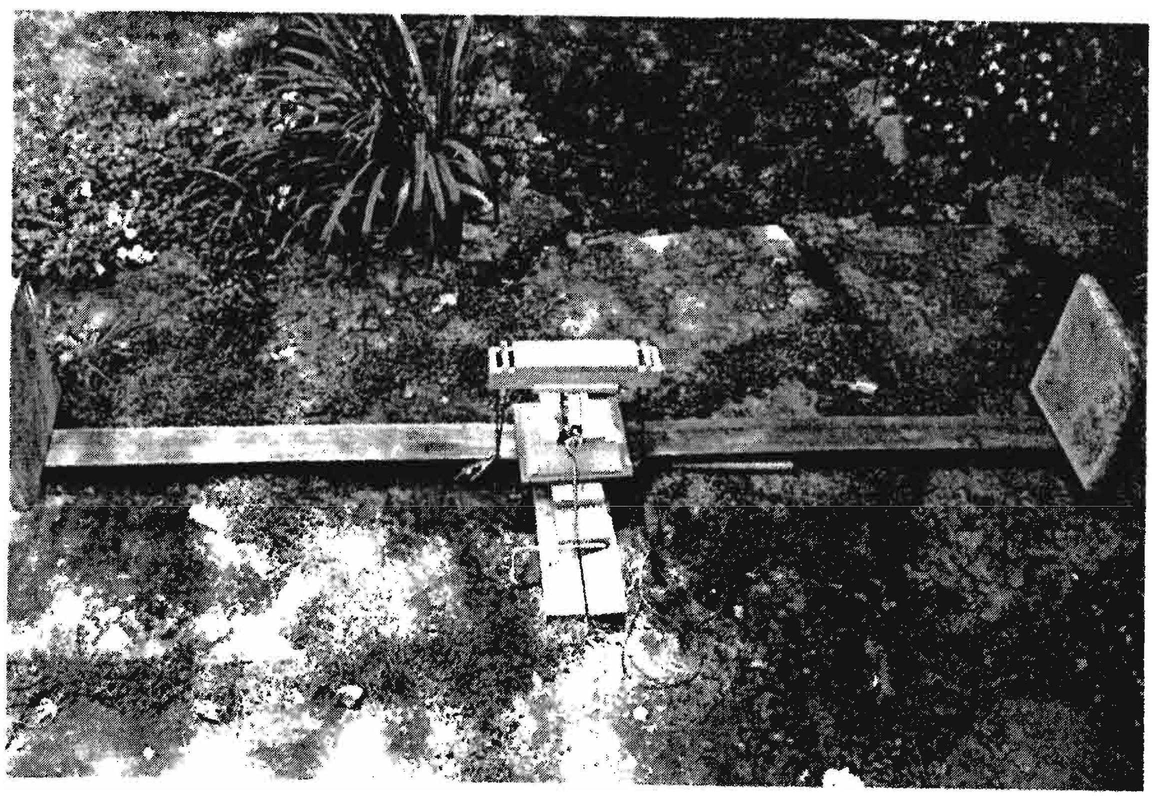


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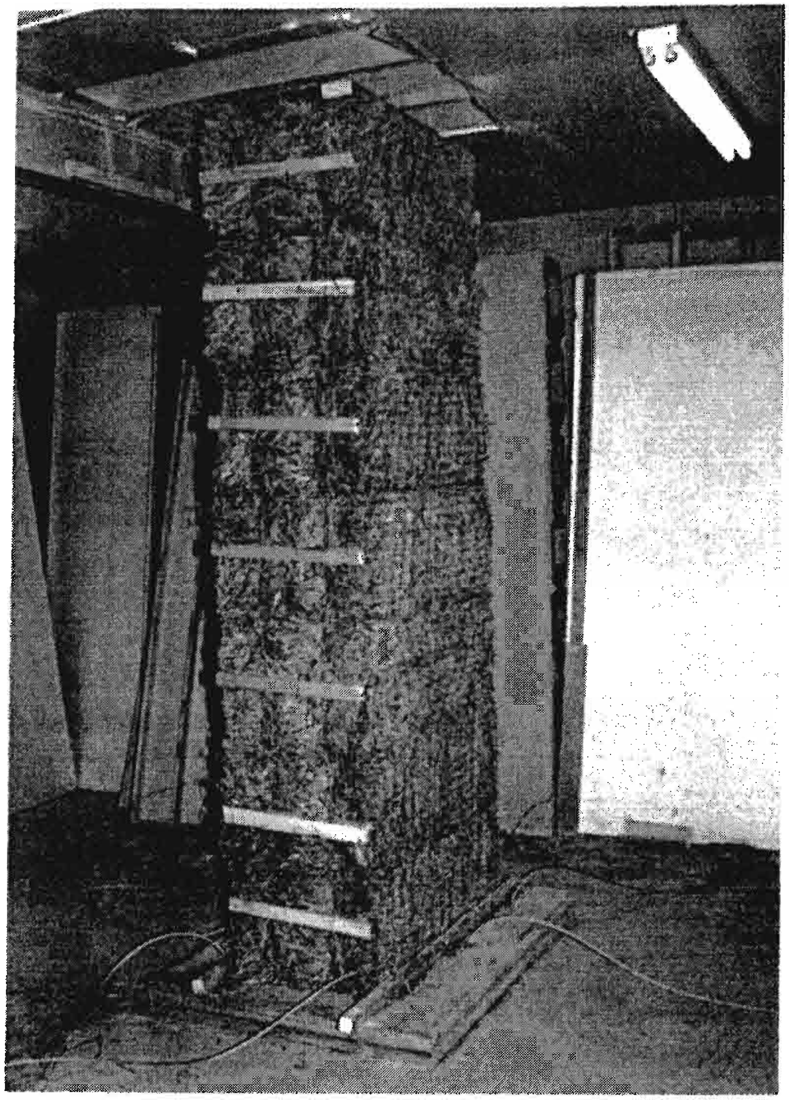
Photo No. 5



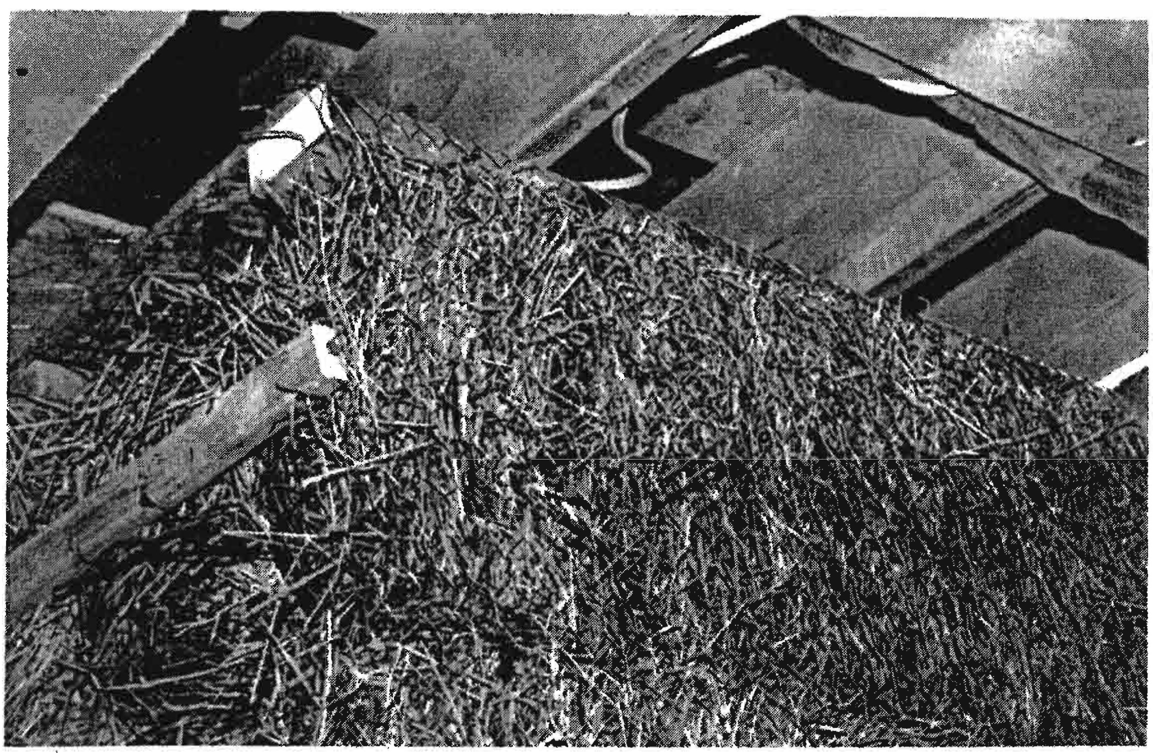


Photo No. 6

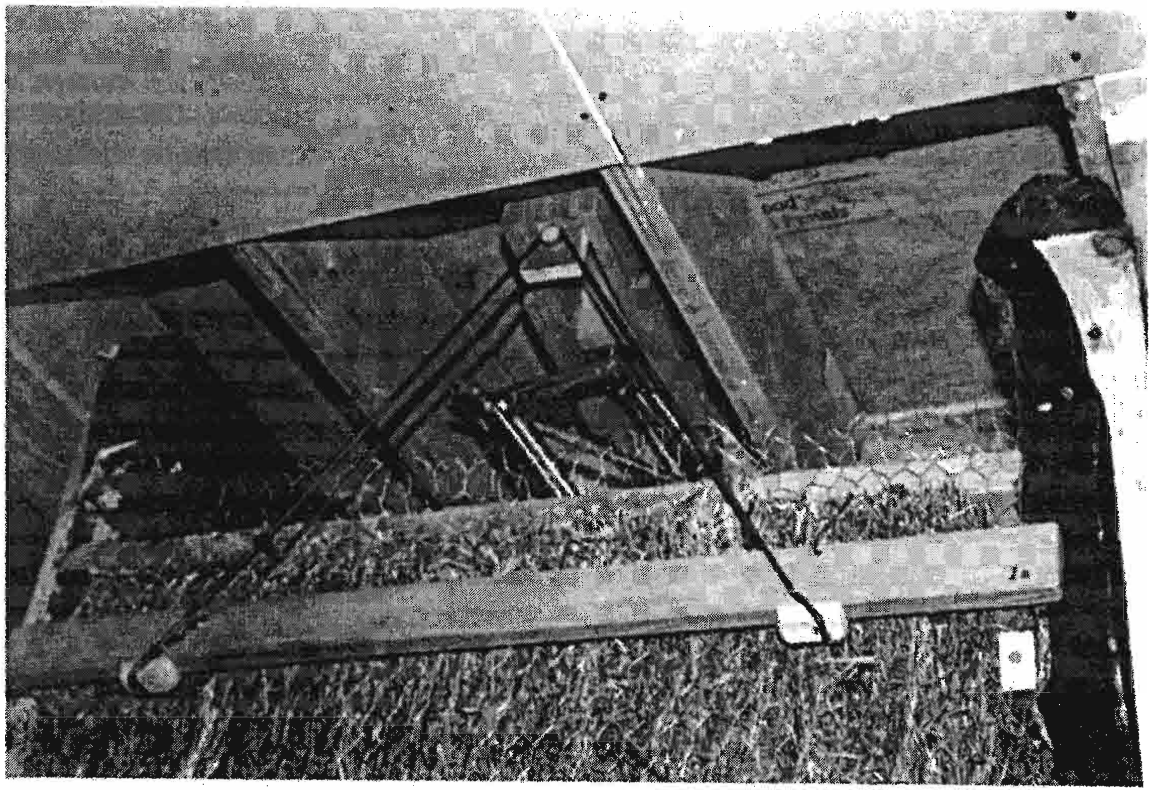


Photo No. 7

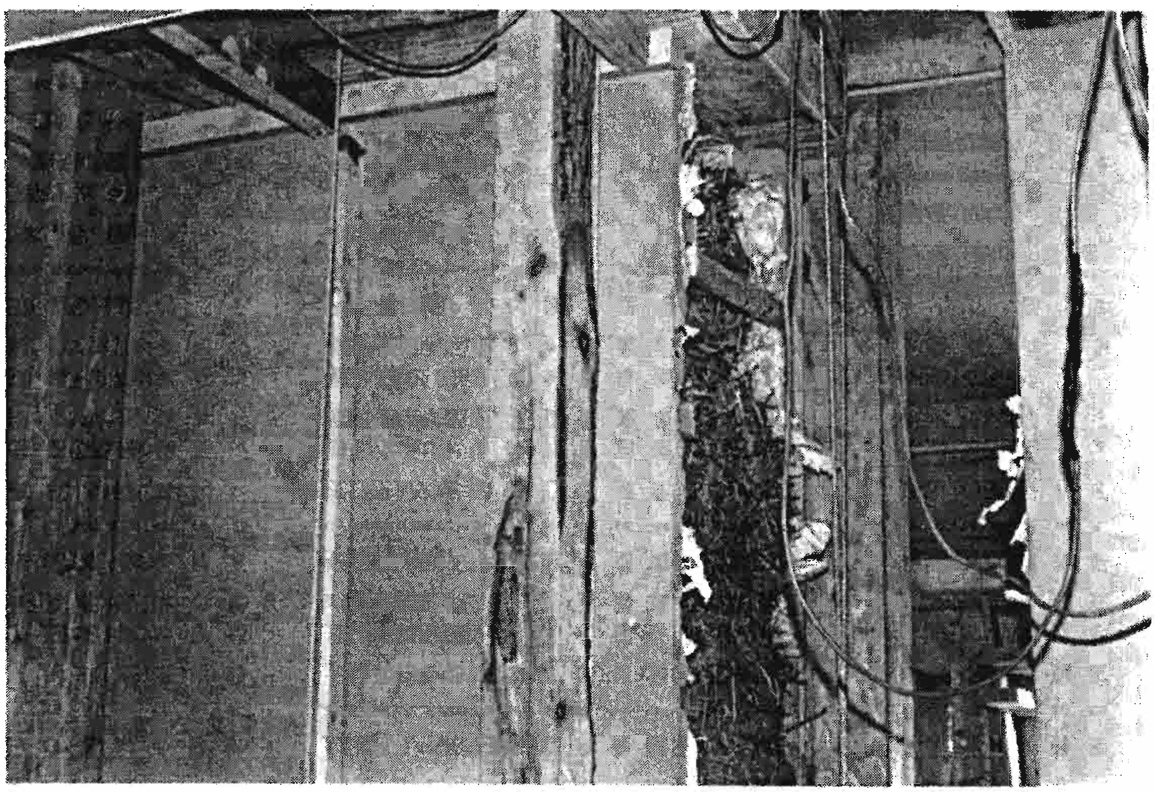
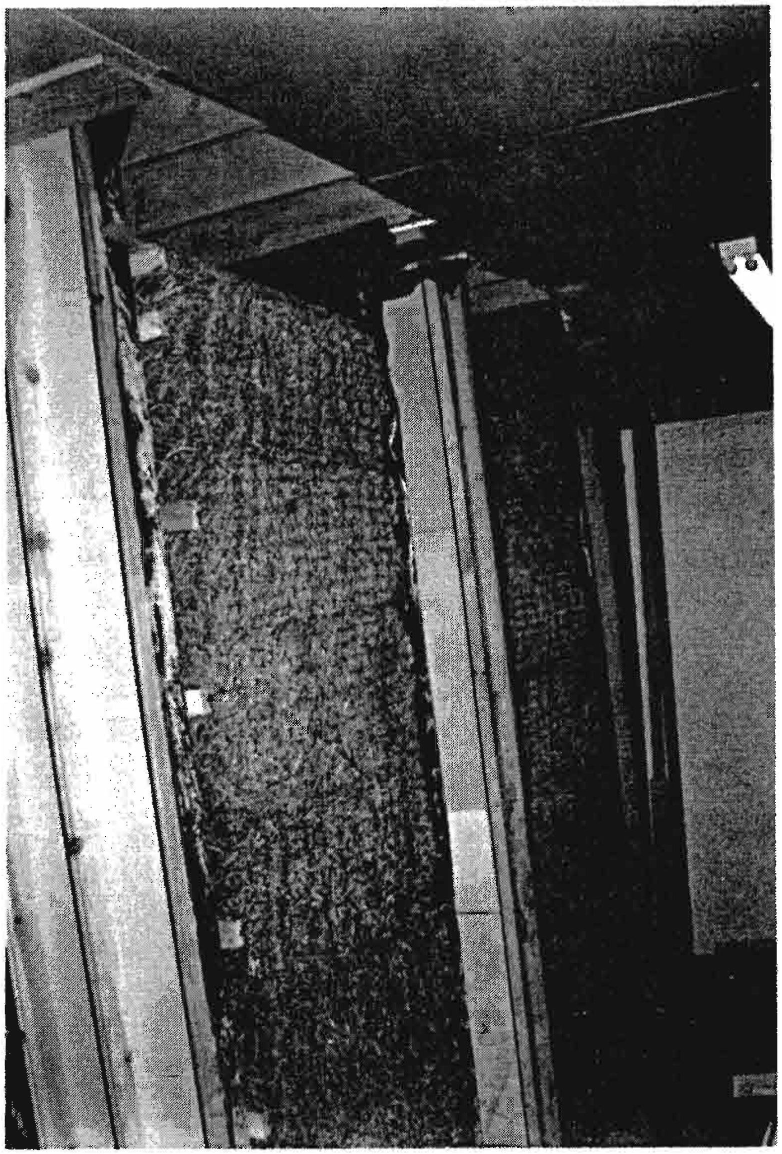


Photo No. 8



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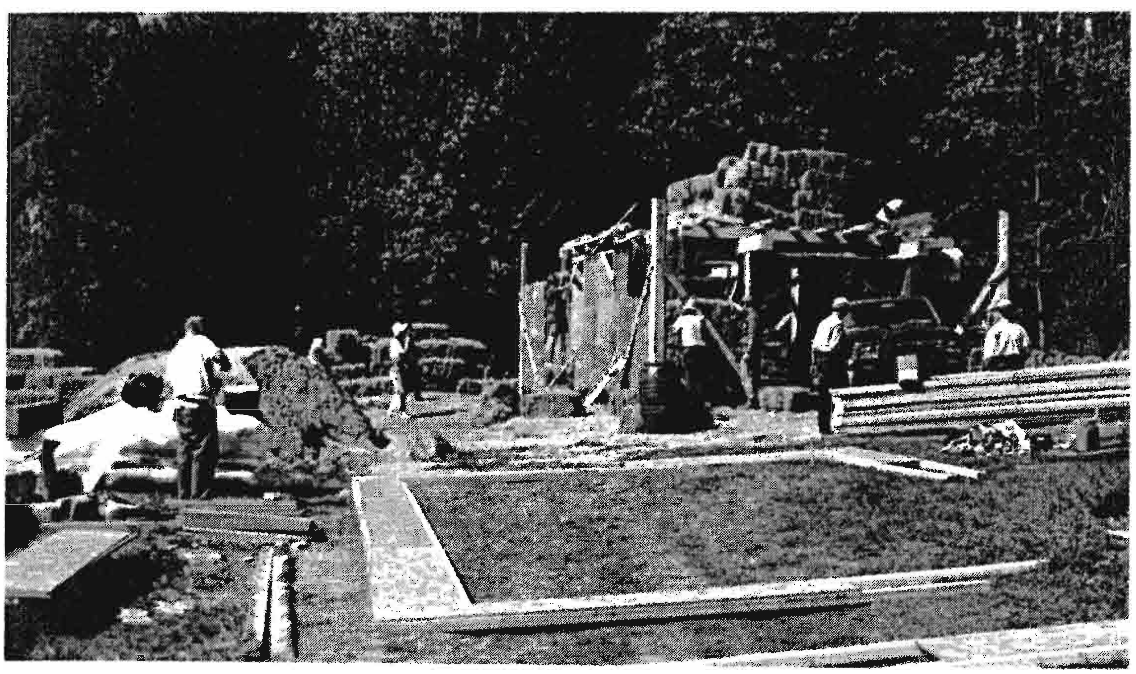

Photo No. 10

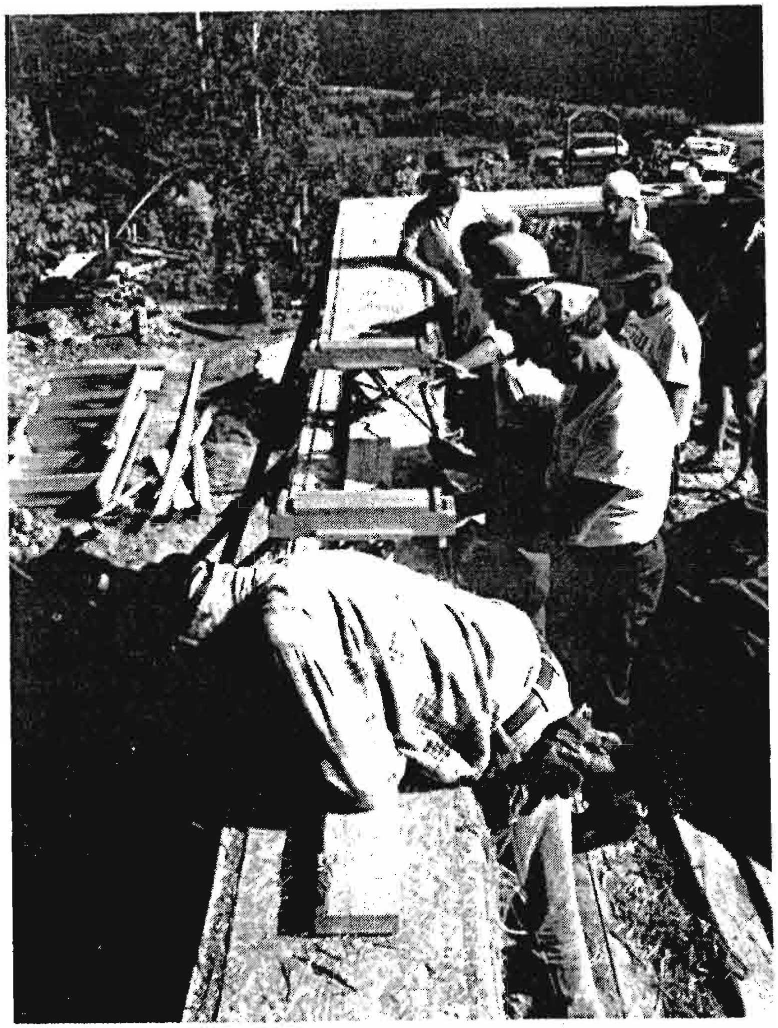

Photo No. 11

Photo No. 12

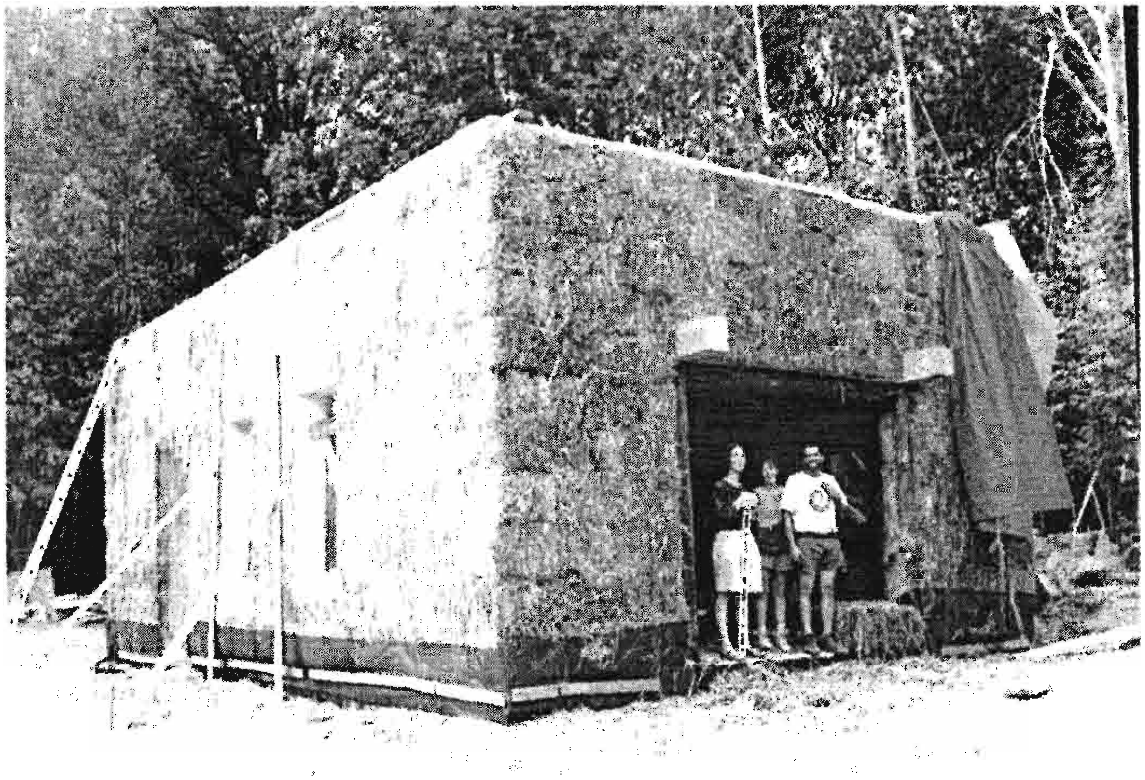

Photo No. 13

Photo No. 14

Photo No. 15