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Structural Design of Built-up Plywood Box Beams

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Structural Design
of
Built-up Plywood Box Beams

A Research Paper for Presentation
to the Graduate Committee
of the
Industrial Technology Department
University of Northern Iowa

In Partial Fulfillment of the Requirements for
the Non-Thesis Master of Arts Degree

by
Michael J. Sneddon

April 14, 1978

Approved by:

Graduate Committee, Chairman

4-26-78
Date

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FIGURES

FIGURES (Cont'd.)

NOTE: There are additional figures in chapter five. They are a part of the student handouts which are designed to be used when presenting box beam design in the classroom. They have not been listed here as they are duplicates of the ones listed above.

Chapter One

INTRODUCTION

What is a Built-up Plywood Box Beam?

The built-up plywood box beam is a structural component using one or more webs of plywood with two or more flanges of lumber. The elements can be glued, nailed, or both, to form a monolithically-acting beam. The unit is hollow except for vertical lumber members placed at intervals to act as web stiffeners. (See figures 1 and 2, pages 2 and 3) The unit is similar to rolled steel sections in that the flanges resist bending while the web(s) transmit(s) shear forces, By using dimension lumber for the flanges and plywood for the webs, the structural properties of the two materials are used to their greatest efficiency. The result is an economical beam with a good weight-to-strength ratio. The box beam is "particularly efficient where deep sections are desired for architectural effects." (American Plywood Association, 1965)

Appropriateness of the Study

As a result of an initial look at the available literature, the researcher discovered that the box beam offers advantages in numerous applications in light frame construction. For the most part, those box beams seen in the Waterloo-Cedar Falls metropolitan area are part of prefabricated, panelized or modular housing, e.g. Wausau Homes, ADR Homes. The question to be answered then was why aren't box beams

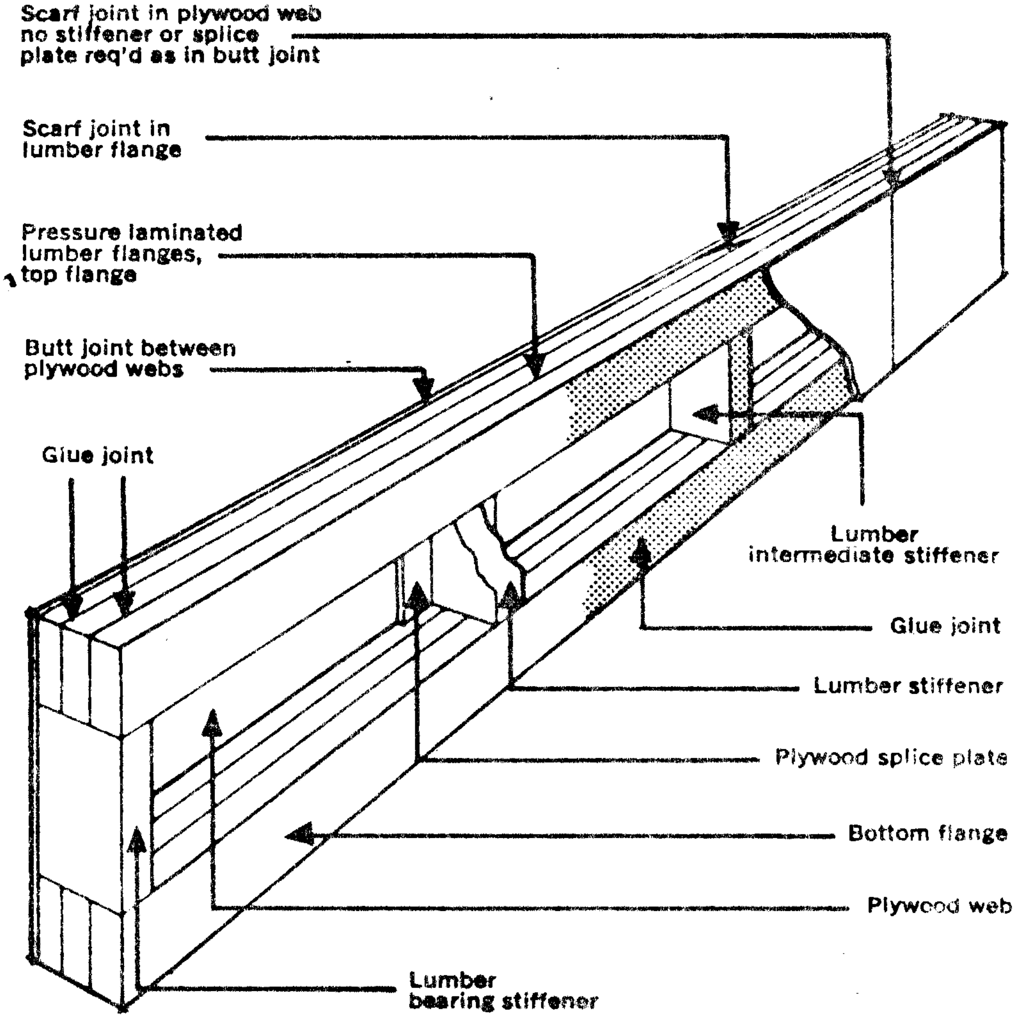


Figure 1

Cut-away View of a Typical
Built-up Plywood Box Beam
(American Plywood Association)

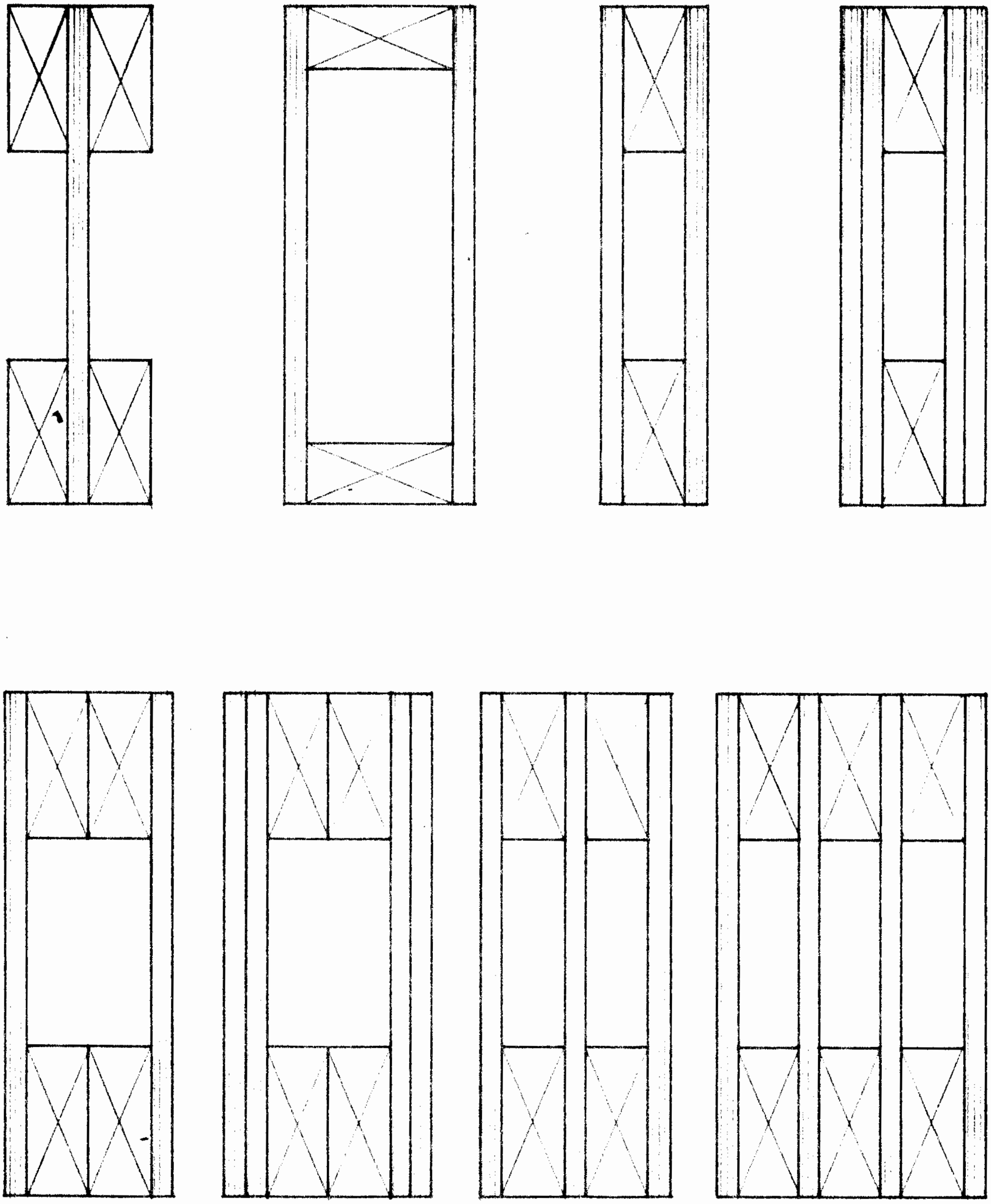


Figure 2

Typical Cross sections of
Built-up Plywood Box Beams

being used by more local builders? Three possibilities came to mind: 1) The box beam is not suited to on-site construction. 2) Builders are not generally aware of the possible advantages the box beam offers. 3) The structural design of box beams is complex and requires engineering expertise.

Research indicated that although shop-built box beams have the advantage of greater quality control with respect to fabrication and materials, site-built units can be successfully and economically built. (Perkins, 1962, pages 90-91)

A field trip seemed to be in order, to investigate hypothesis number two. Tri-Square Builders of Hudson, Iowa is engaged in home building and light commercial construction. They enjoy a most favorable reputation in that community for quality construction and innovation in design and construction techniques. The researcher talked with Mr. Leigh Bemus, Tri-Square's President. Mr. Bemus acknowledged that they have used plywood box beams on occasion and would like to use more of them as he felt their use allowed them increased flexibility in both design and economy. Tri-Square's crews have overcome their reluctance and are now more enthusiastic about building box beams. Mr. Bemus stated that his lack of structural design ability and the absence of convenient design tables have prevented their firm from using the box beam more extensively.

Further investigation pointed up the validity of Mr Bemus' last remarks concerning the safe design of this type of beam. One must be proficient in basic statics and strength of materials before undertaking the rational design of such a structural member. Apparently hypothesis number three is a critical factor.

The researcher was able to find several "design tables" for the box beam. They fell into two general categories. Either they still required a fair understanding of the underlying engineering concepts or they were for very specialized applications, e.g. garage door headers. The builder then, is still quite limited in his use of box beams unless he or she possesses the necessary skills to make safe decisions using the more complex tabular data.

The researcher, being involved in the education of architectural technicians, teaches a course in structural wood design. It seems quite appropriate then, that a study of plywood box beam design would make a logical and valuable addition to such a course. It also follows that the career opportunities of the architectural technician, familiar with box beams and their design, would be enhanced.

Purpose and Scope

The purpose of this study, given the background mentioned above, is to investigate the structural design of built-up plywood box beams and to develop an instructional unit based on their design.

The scope shall be limited to statically determinate beams with either uniformly distributed loads or typical girder loadings.

The resulting instructional unit will be designed as an addition to a course in structural wood design at the vocational-technical/community college level.

Protection

The researcher is aware that the instructional unit to result from this study, perhaps, should be protected. The most appropriate method for such printed material would be through copyrighting.

It was discovered that the copyright law recently underwent a major change. Public Law 94-553 was signed into law on October 19, 1976 and went into effect on January 1, 1978. It represents the first major change of the copyright laws since 1909. Under the new law, both published and unpublished materials are covered under the federal copyright laws. Protection will be for a period equal to the author's life plus fifty years. (Schick, 1977)

Appendix A (Pages 94-98) contains a copy of the application form for published written material. Page four of that document (page 98) indicates the procedure to use in securing such a copyright. This form will no doubt be ammended to include unpublished material, previously protected under common law.

It is not the intent of the researcher to procede with the steps outlined on that document, at this time. More logically, the instructional unit will be tested in a classroom situation and modified as required. If, after such modification, the researcher feels that the material is of sound educational value, appropriate action will be taken.

Definition of Terms

The terms below are ones that the architectural technician should be familiar with by the time an attempt is made to design plywood box beams. They are defined here for the purpose of review.

BENDING MOMENT: "The moment which produces bending at a section of a beam or other structural member; equal to the sum of the moments taken about the center of gravity of that section." (Harris, 1975, page 50)

BENDING STRESS: In a simple beam having a load, fibers above the neutral axis are in compression, fibers below the neutral axis are in tension, together they are called bending stress. These stresses are zero at the neutral axis and at a maximum at the extreme fibers of the section.

BENDING DESIGN: The usual first step in beam design; selecting a beam whose resistive moment is equal to or greater than the bending moment the beam is subjected to. This insures that the bending stresses are not excessive for the beam's material.

COMPRESSIVE STRESS: When a compressive force is applied to a material, the fibers are shortened and are said to be under stress.

DEAD LOAD: The weight of a structure, including the weight of fixtures and equipment permanently attached is designated dead load.

LATERAL DEFLECTION: Horizontal movement of a beam or girder is said to be deflecting laterally.

LIVE LOAD: The moving or moveable external load on a structure is called live load. The live load of a floor would be such things as furnishings, people and the like. Roofs are subjected to live load because of wind and snow.

MODULUS OF ELASTICITY: "In an elastic material which has been subject to strain below its elastic limit, it is the ratio of the unit stress to the corresponding unit strain." (Ibid. page 320) It is a measure of a material's stiffness.

MOMENT: A moment is the tendency for a force to cause rotation about a point or axis. The magnitude of a moment is equal to the magnitude of the force multiplied by the distance from the force to the center or axis.

MOMENT OF INERTIA: The moment of inertia is a measure of a body's resistance to movement when acted upon by a force. It is equal to the sum of the products obtained by multiplying each of the infinitely small areas by the square of their distances from the section's center of gravity. This can be represented algebraically: $\sum az^2$.

RESISTIVE MOMENT: It is the product of a beam's section modulus and the beam material's allowable bending stress.

SECTION MODULUS: This is a measure of a beam's flexural strength. It is equal to the section's moment of inertia divided by the distance from the neutral axis to the farthest point in the section. (This distance is designated as "c" in algebraic formulas.)

SHEAR: In a beam, the tendency for parallel planes to slide past each other when acted upon by a force is called shear.

STATICAL MOMENT: This is the moment of a plane surface (area). It is equal to the product of an area of a section and the distance from the section's center of gravity to the center of moments.

STATICALLY DETERMINANT BEAM: This is a beam that can be analyzed by using the laws of statics alone.

STRUCTURAL MECHANICS: This involves the sciences of mechanics (statics and dynamics) and strength of materials. This is the basis of structural design.

TENSILE STRESS: This is a stress that results when a force is applied to a body in such a way that it tends to elongate or "pull apart" the fibers in the body.

Chapter Two

BOX BEAMS - GENERAL INFORMATION

Uses and Advantages

> ...Plywood box beams are opening new horizons for building design each day. A highly versatile component spanning distances up to 120 feet, they utilize the structural soundness and inherent physical properties of plywood to achieve new and economical building concepts. (Plywood Fabricator Service, 1959)

Plywood box beams have been used in almost every type of construction. Most often they find service as roof and floor beams, exposed rafters, lintels and ridge beams. However they have served as structural members for conveyor belts, pedestrian bridges and sign mountings. (DFPA, 1958, page 6) Weather does not restrict the usage of the box beam. They may be used in places of permanent exposure to extreme weather. With special treatment, they may be used where fire resistivity or decay is a concern. (Ibid.) Many of the problems of building maintenance encountered with solid wood members are prevented or minimized by using box beams. Seasoning defects and dimensional stability are but two examples. (Ibid.) Box beams can be built in various shapes, such as cambered, curved, arched, or tapered, as well as the more conventional straight beam of rectangular cross-section. (Perkins, 1962, page 90)

The Plywood Fabricator Service (1959) lists ten distinct advantages that the box beam has to offer. These advantages are listed on the following page.

- Great design freedom
- High strength and stiffness to weight ratios
- Rustproof and corrosion resistant
- Dimensional stability
- Freedom from large shrinkage cracks
- Smooth, easy-to-finish surfaces
- Reduced transportation costs
- Uniform manufacture
- Rapid delivery
- Low in-place costs

Fabrication

Box beams may be assembled using glue, nails, or a combination of both. Metal connectors may be used to laminate immediately adjacent flange members. Flanges may be placed either vertically or horizontally. (See figure three, below)

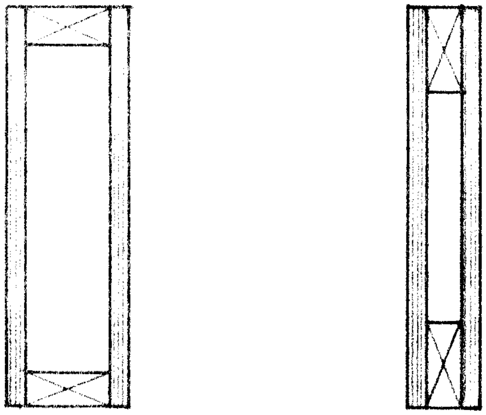


Figure 3

Box Beam Cross Sections Showing
Vertical and Horizontal Flanges

Shop fabrication is recognized as the preferred construction practice. This permits full-pressure gluing. Although this requires expensive equipment, the resulting beam acts as a completely integral unit, with no slippage at joints or splices. This method also insures that stresses may be safely assumed up to the capacity of the plywood with respect to rolling shear. (Perkins, 1962, page 91)

Nail-gluing can yield satisfactory results also. However, if the beam is site-built, particular attention must be placed on good gluing and nailing techniques, appropriate moisture content of the lumber and the like. (Ibid.) The design of nailed and glued members is the same as for glued only; the nailing is used to develop enough pressure to permit proper glue-line integrity.

The third recognized method of fabrication is nailing alone. This is the simplest and most economical method. Nail bearing strength is used to transmit shear stresses at web-to-flange joints. If shear stresses are moderate, as in most light frame construction applications, the system performs quite adequately. (Ibid.) Since no glue is used, rolling shear stress is not a design consideration; however, the nailing schedule is quite critical. (Moore, 1978) Nails having larger-than-normal heads and/or deformed shanks may be used to increase the bearing capacity of each nail, thereby permitting a wider nail spacing. (Perkins, 1962, page 91)

Figures four through eight, on the pages following, illustrate the steps in fabricating and installing a built-up plywood box beam.

Figure 4

Box Beam Fabrication:
Lumber Members Cut to Size,
Adjacent Flanges Laminated

Figure 5

Box Beam Fabrication:
Lumber Members Nailed or
nail-glued together

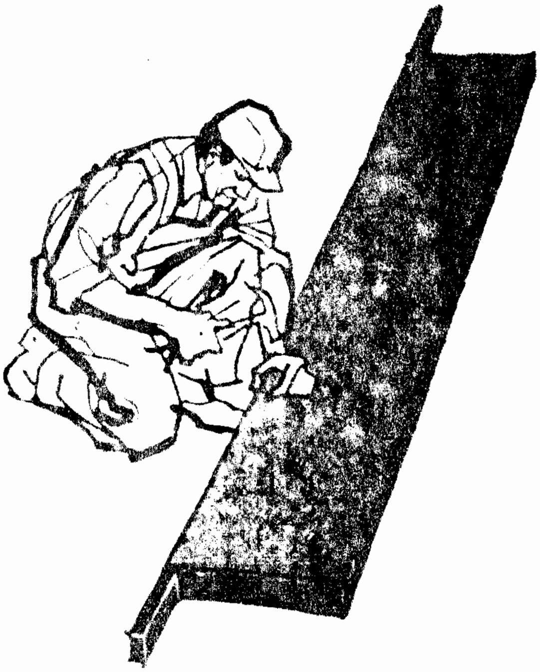


Figure 6

Box Beam Fabrication:
Laminating Plywood Web
Members to Lumber Members

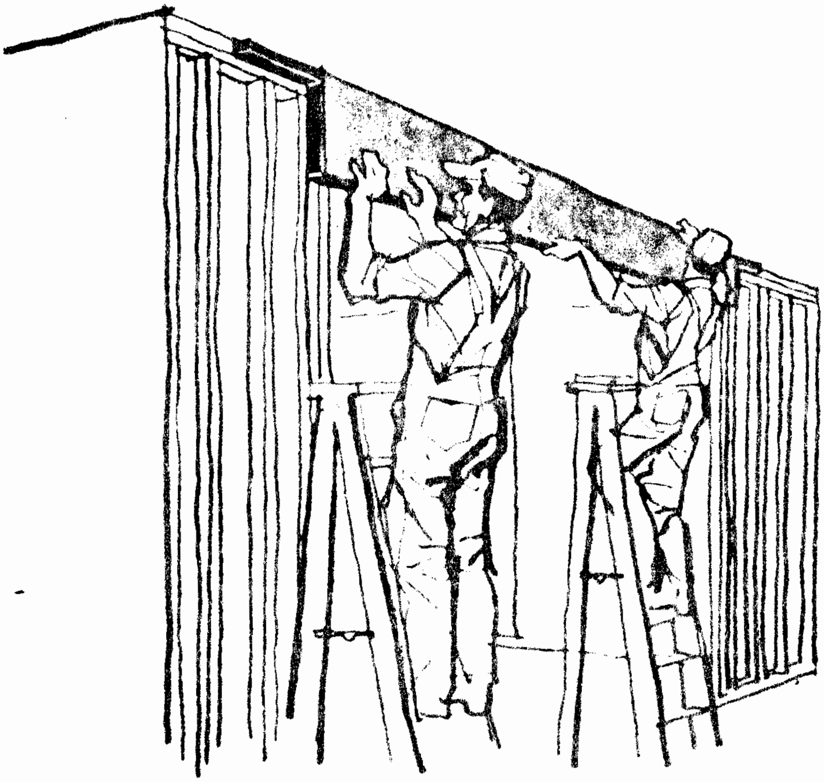
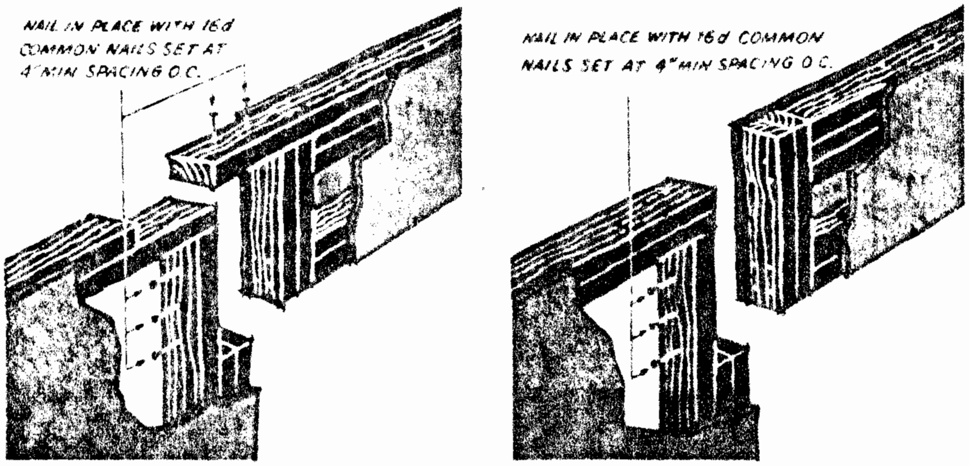


Figure 7

Box Beam Fabrication:
Lifting Completed
Beam into Place



■ *Suggested Installation*

NAIL IN PLACE WITH 16d COMMON NAILS SET AT 4" MIN SPACING O.C.

■ ***Alternate Installation***

NAIL IN PLACE WITH 16d COMMON NAILS SET AT 4" MIN SPACING O.C.

Figure 8

Box Beam Fabrication:
Installation Details

Mass Production

As stated previously, box beams for frame construction may be either site-built or shop-built. Those used in industrialized housing are, in fact, mass produced. The researcher visited the Wausau Homes Plant in Ottumwa, Iowa (not in conjunction with this study) and observed the mass production ob box beams and stressed-skin panels. Of particular note was the method they used for speeding the glue-curing process. A small gauge copper wire was positioned in the glue bead as it was placed on the lumber members. After the plywood was put in place and secured (pnuematically nailed), the ends of the copper wire were connected to an electrical charge for the purpose of applying heat to the glue joints, thus quickening the curing. After a predetermined amount of time, the ends of the copper wire were clipped and the component was complete.

Chapter Three

BACKGROUND

An historical view of the built-up plywood box beam, to be meaningful, should include a brief history of plywood and its forerunner, veneered wood.

Veneering

Manufacturing plywood is a process consisting of placing wood veneers (thin layers) together using heat, pressure and an adhesive substance. Adjacent layers are placed so that their grain structures are at right angles to each other. Relatively speaking, this is a new process. Fundamental to the making of plywood is veneer; the art of veneering is indeed quite old.

The earliest known use of veneer dates back to ancient Egypt. In the sculptures of Thebes, thought to have been built around 1500 B.C. there is a mural depicting men engaged in veneering. There are even a few pieces of veneered Egyptian furniture still intact, having been discovered in sealed tombs during the 1800's (Perry, 1942, page 20-21)

The use of veneer can be traced from Egypt down through ancient Greece and the Roman Empire, to seventeenth and eighteenth century France. There were many pieces of furniture made during this period that are, in fact, art masterpieces. A prime example of beauty in veneered wood is the "Bureau du Roi" built for Louis XV at a cost of over a million francs, taking nine years to complete. This particular piece, the predecessor of the roll-top desk is considered to be <u>the</u>

plywood masterpiece. (Ibid.)

The use of veneer became more popular and less expensive with the advent of machines to aid in cutting veneer; coming during the late eighteenth and early nineteenth centuries. (Ibid., pages 23-26)

Early Plywood

The best record of the first plywood, as we know it today, is in the form of a patent. John K. Mayo of New York City was granted patent number 51,735 on December 26, 1865. (Ibid. page 26) Following is the description that appeared on that patent:

> The invention consists in cementing or otherwise fastening together a number of these scales or sheets, with the grain of the successive pieces, or some of them, running crosswise or diversely from that of the others... The crossing or diversification of the direction of the grain is of great importance to impart strength and tenacity of the material, protect it against splitting, and at the same time preserve it from liability to expansion and contraction.

You will notice that the word "plywood" is absent from the quotation above. The term "plywood" did not come into use until several years later. During the interim, the product was referred to as "veneer". (Ibid. page 27)

Early plywood was used, for the most part, in place of veneered wood. The first new applications of plywood was in the construction of pianos, organs and sleighs. The first use of plywood in building construction was apparently in making doors, in or about the year 1890. (Ibid. pages 28 -31) Product designers were taking advantage of the material's dimensional stability.

Plywood veneer cutting originated in this country about 1890 in Tacoma Washington. Douglas Fir plywood, now a major species, did not appear until 1905. There were some Douglas Fir plywood panels exhibited in 1905 at the Lewis and Clark Exhibition in Portland Oregon. These panels were essentially hand-made. Mechanical production of Douglas Fir plywood began in 1910, being used in the manufacture of doors. (Ibid. page 33)

The word "plywood" came into existance generally, during World War I. The change in name from "veneer" to "plywood" proved to be a boon to its manufacture. One of the handicaps the material suffered under its old name was the connotation that the dictionary gave to the word veneer - "a superficial or meretricious show" (Ibid, page 35). The Forest Products Laboratory in Madison Wisconsin (a division of the Forest Service of the United States Department of Agriculture) appears to have been instrumental in the name change. In 1919 the Veneer Association was supplanted by the new Plywood Manufacturers Association. (Ibid. page 36)

Structural Plywood

Plywoods are made from both major classifications of wood - softwoods and hardwoods. Softwood species are the ones used to manufacture structural plywood.

The first plywood that could be considered structural was the Douglas Fir panels mentioned earlier. World War I was largely responsible for the rapid advancement of the aviation industry. This influenced the plywood industry also as aircraft manufacturers relied extensively on the structural stength and light weight qualities of thin plywood. (Wood, 1943, page 6)

The superiority of plywood over conventional lumber, with respect to shear strength was recognized quite early. The Industrial

Arts Index (later renamed the Applied Science and Technology Index) of 1920 listed an article entitled "Shear Strength of Plywood Webs". The researcher however, was unable to locate the October, 1920 issue of Mechanical Engineering to verify the article's contents.

One of the problems with the plywood of this early era was the poor performance of the glue when subjected to moisture. (Wangaard, 1953, page 128) The plywood used in airplanes was generally protected from moisture by fabric and doping substances. Chemists all over Europe and this country set out to find a solution for this problem. (Wood, 1943, page 6) A moderately moisture-resistant soy bean glue was developed in 1923. This glue was used in the manufacture of Douglas Fir plywood. This plywood, although structural, was best suited to interior applications. (Wangaard, 1953, page 129).

Apparently for a time, there was a reluctance on the part of some to believe that plywood could be used for widespread structural applications. The Forest Products Laboratory published a report in 1929 entitled The Rigidity and Strength of Frame Walls. In this report there was no mention of plywood. A supplement to that report, published in 1934, did recognize plywood as an alternative wall sheathing material. (Ibid.)

A real breakthrough came in the mid-1930's when a waterproof thermosetting phenolic resin adhesive was developed. This made possible the production of exterior grade plywood. (Ibid.)

As previously reported, Douglas Fir plywood came to dominate the plywood industry. In 1938 the Douglas Fir Plywood Association (DFPA) was organized. It was made up of manufacturers of Douglas Fir plywood (and other species, at a later date). The organizations's purpose was to encourage the use of plywood by conducting research and development work.

In 1925, the plywood industry produced 200 million square feet of plywood - all interior grade. Twenty-five years later, production figures had grown to nearly three billion square feet - of which 800 million were classified as exterior grade plywood. (Ibid.) These figures, as far as the researcher could tell, include only softwood plywood. By 1968, the production of softwood plywood in the United States surpassed the fifteen billion square foot mark. (Hoyle, 1973, page 49)

NOTE: See appendix B (page 99-104) for information about typical plywood sizes, terminology and grading criteria.

Engineered Plywood Components

The most common uses of structural plywood in light frame construction is wall and roof sheathing and subflooring. These uses however do not fall into the category of "engineered plywood components." This is not to say that engineering research and testing is not carried out with respect to these uses.

The diaphragm, shear wall and folded plate are typical structural systems that may involve the use of plywood.

Engineered plywood components are for the most part, prefabricated assemblies using one or more materials in conjunction with plywood. Their use has come about because of the significant increase in shop fabrication of building components. Typically these include stressed-skin panels, trussed rafters and joists, rigid frames, folded plates and box beams. (Perkins, 1973, page 75) The researcher is aware of referring to the folded plate as both a system and a component. The decision as to what to call it depends on whether the folded plate roof is built on-site, as a system, or fabricated in units and installed at the site.

The use of components has had an effect on building construction in terms of economy and design. Erection time has been shortened, while flexibility has increased. Most engineered plywood components use dimension lumber, glue and plywood; they have gained a rather wide acceptance. The several reasons for this include plywood's light weight along with the ease of fabrication and attachment to the other elements in wood construction. (Ibid.) Its weight-to-strength ratio also makes it very competitive with other types of structural members.

Nelson Perkins (Ibid.) reminds the builder that several of the plywood components require engineering design and skilled fabrication techniques. DFPA made available this technical assistance through the Plywood Fabricator Service (PFS), a non-profit organization set up in 1959. Through the efforts of PFS, plywood components such as the box beam are now recognized by many of the model building codes. (Ibid.) Waterloo and Cedar Falls Iowa have adopted the Uniform Building Code as published by the International Conference of Building Officials. Sections 2513 and 2514 of this code address the use of plywood components.

The historical front-runner of plywood components was the stressed-skin panel. (Vermilya, 1961, page 94) It was developed during the 1930's at the Forest Products Laboratory. The panel was used extensively in the prefabricated housing market during the Second World War. (Perkins, 1962, page 76) Wausau Homes is one of the present-day manufacturers that continues to use the stressed-skin panel in their floor and roof construction.

The built-up plywood box beam was developed shortly after the stressed-skin panel, again largely due to the efforts of the Forest Products Lab. (Ibid.) The concept of the box beam was used in the United States for aircraft wing beams and struts in the 1920's. In fact the box beam research initially conducted at the Forest Products Laboratory was done under the direction of the National Advisory Committee on Aeronautics. (Ibid. page 89)

During World War II, research in Germany concentrated on wood construction, glues, and other fastening techniques for wood because much of the steel had been diverted into war materiel. Similar research was stimulated in the United States for the same reason. The result was the development of metal framing anchors and "glu-lam" construction. The box beam was one of the construction techniques to benefit from that research. (Ibid.)

One of the early publications dealing with the box beam is Section Nine of Technical Data Handbook, "Design of Built-up Beams with Plywood Webs" published in 1942 by the Douglas Fir Plywood Association. (Ibid.) Unfortunately the researcher was unable to obtain a copy of this document. Information about box beams also began to appear in periodicals. The March 1944 issue of Scientific American noted that box beams have advantages to offer the builder. The article stated that this "new product...has been developed by Timbeam, Inc." The researcher was unsuccessful in his attempt to find out more about the Timbeam company, possibly the first to commercially construct box beams.

The periodical indices revealed several related articles written during the time the box beam was being developed. The follwing page lists several of these articles; they were not found by the researcher. They have been included here, should the reader have access to a more extensive library than that of the University of Northern Iowa and Hawkeye Institute of Technology.

Engineering News	"Plate Girders of Plywood" October 15, 1936
Civil Engineering	"Plywood and Laminated Timber Construction" January 1940
Engineering News	"Plywood Girders Roof a Warehouse" April 23, 1942
Engineering News	"Plywood Plate Girders" November 4, 1943
Civil Engineering	"Design of Built-up Plywood Panels" September 1944
American Society of Civil Engineering Proceedings	"Design of Plywood I Beams" June 1946

Geographical History

The researcher found little information with respect to the geographical aspect of the box beam's past. Scientific American (March 1944) mentioned that plywood box beams "are now being used extensively in the Middle West." This statement should be viewed as not surprising since much of the research and development of box beams was carried out by the Forest Products Lab which is in Madison Wisconsin. The researcher is of the opinion that such geographical confines no longer exist; due in part to the efforts of the DFPA and presently the American Plywood Association. These organizations have spent considerable effort in promoting the box beam as one of the economical and advantageous uses of plywood.

Chapter Four

BOX BEAM DESIGN

The main purpose of this study is embraced by this chapter - the sturctural design of built-up plywood box beams.

Assumptions

As stated earlier, it is the researcher's intent that this study result in the development of an instructional unit. The study is to be incorporated into a structural wood design course at the post-secondary level. Therefore, the technical information presented herein is prefaced with the following assumptions:

1. The reader understands the fundamentals of structural mechanics (statics and strength of materials).
2. The reader is familiar with basic design of statically-determinant flexural members.

Design Method

The researcher found a few references, texts, etc. which explained box beam design methods. Many of these procedures were similar in that they were somewhat simplified, abbreviated or narrow in scope of application. The researcher has chosen to use the most accurate, comprehensive and up-to-date design procedure available, keeping in mind that is should be appropriate for study by architectural technicians. Robert Hoyle's Wood Technology in the Design of Structures (1973) presents the best information the researcher was able to find.

Mr. Hoyle made reference several times to _Plywood Design Specification, Supplement Number Two on Design of Plywood Beams_, published by the American Plywood Association. The researcher has written the APA and requested a copy of that document as it was not found locally. As of this writing, the information has not been received.

The researcher, in attempting to purchase a copy of _Wood Technology in the Design of Structures_, learned that Mr. Hoyle has written a revised, up-dated edition. The publishers, Mountain Press of Missoula Montana, informed the researcher by mail that the new edition would be available soon. The tentative price is $12.50.

In light of the facts mentioned above, the main source for the technical portion of this study is the 1973 edition of Hoyle's _Wood Technology in the Design of Structures_.

Procedural Outline

The design procedure that will be followed in this study can be outlined as follows.

I Loading
  A. Dead loads
  B. Live loads
  C. Type of loading
II Trial Assumption
  A. Material specifications
  B. Trial section
    1. Configuration
    2. Dimensions
    3. Section properties

        a. Gross moment of inertia
        b. Net moment of inertia
        c. Section modulus
        d. Statical moment
        e. Weight per linear foot

III Bending Investigation
    A. Resistive moment
    B. Bending moment
    C. Modification of trial assumption

IV Shear stress investigation
    A. Through-the-thickness (Horizontal shear)
    B. At flange-web joints (Rolling shear)

V Deflection investigation
    A. Approximate
        1. Due to bending
        2. Due to shear
    B. Refined shear deflection

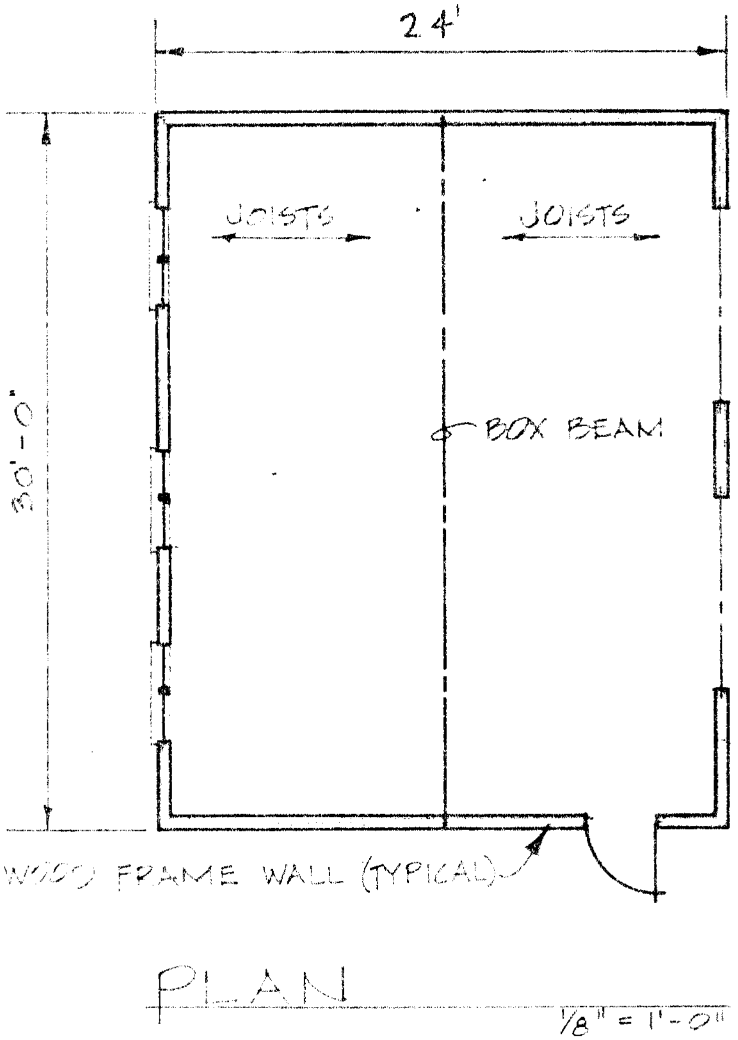
VI Web stiffeners
    A. At reactions and concentrated loads
    B. Uniformly distributed loads

VII Lateral Stability

Sample Problem

Each of the items in the outline above will be explained by using the following sample problem.

The designer wishes to clear span the roof of the building shown in figure 9 (See page 27). The cost of transporting prefabricated roof



ROOF CONSTRUCTION:

3 PLY BUILT-UP ROOF
3/4" EXTERIOR PLYWOOD DECKING
2x10 JOISTS @ 2'-0" O.C.

Figure 9

Sample Problem:
Plan View of Building

trusses to the remote site would prove too costly, consequently, the decision has been made to place a job-built built-up plywood box beam along the building's longitudinal axis. This box beam will support roof joists placed at two foot centers.

Loading

Recognizing that the beam in this application is a simply-supported member, having a uniformly distributed load, the designer will first need to determine the magnitude of the load.

In this case, the dead loads consist of:

Built-up roofing	= 5.5 PSF
Plywood decking	= 2.0
Joists	= 3.5
	11.0 PSF

The live load will depend on local building codes. The designer should consult the appropriate code, or if none are in effect, select a live load from reference material, appropriate to the region. For purposes of this sample problem, thirty pounds per square foot will be used.

Therefore: Total design load (PSF) = 11 + 30 = 41 PSF

In this typical application, the area of roof supported by the beam is equal to the beam span multiplied by the sum of half the joist span on both sides of the beam.

For the sample problem: 30' x 12' = 360 square feet

Therefore the total superimposed beam load is:

360 square feet X 41 PSF = 14,760#

Trial Assumption

The design process for box beams is to assume a member and then verify its structural integrity. This assumption has two main parts, selection of material and selection of a section.

Material specification. Materials must be specified for flange members and web members.

The dimension lumber used in the flanges may be specified in more than one manner. The designer may wish to call out species, grade, moisture content, etc. and use the appropriate design values assigned to his selection by the appropriate grading agency. (See appendix C, page 105-109) The designer's selection should obviously be one that is available locally, at reasonable cost. An alternative to this method is for the designer to specify minimum values for bending, tension, compression, shear, modulus of elasticity, etc., without calling out a particular lumber species and grade.

Plywood is specified by calling out a particular grade and species group. Typically, plywood used in box beams are group one species of types having exterior glue. (See appendix D, page 110 for allowable stresses in plywood.)

The reader should refer to appendix F (Page 114) for a suggested specification for plywood box beams.

For purposes of the sample problem, the researcher makes the following assumptions for material specifications:

Lumber: Douglas Fir/Larch, Select Structural Joists & Planks

Tension, parallel to grain (F_t) = 1200 PSI

Compression, parallel to grain (F_c) = 1400 PSI

Compression, perpendicular to grain ($F_{c\perp}$) = 455 PSI

Modulus of elasticity = 1,800,000 PSI

Plywood: Douglas Fir (Group 1), Structural I - AC

Tension, parallel to grain (F_t) = 2,000 PSI

Compression, parallel or perpendicular to grain = 1650 PSI

Shear, in plane perpendicular to plys = 250 PSI

Shear, in plane of plys (rolling) = 75 PSI

Modulus of Elasticity = 1,800,000 PSI

Trial section. The researcher found tables that were designed to help the designer in making an assumption for the size and configuration of the trial section. However because of the virtually unlimited number of possible configurations, these tables were necessarily incomplete. The task of making this assumption becomes easier with experience. As with beams of steel or concrete, the deeper beam is usually the more economical choice. Plywood box beams are typically limited to a depth of four feet, as commonly available plywood panels are four feet in width. There may be other considerations which dictate the physical dimensions of the beam section. See figure ten on page 31 for the researcher's trial section.

The next step is for the designer to calculate the structural properties of the trial section. This includes moment of inertia (both gross and net), section modulus, statical moment and section weight (in pounds per linear foot).

Computing the gross moment of inertia is accomplished exactly in the same manner as it is for any built-up section. The gross moment of inertia is needed when calculating the box beam's deflection due to

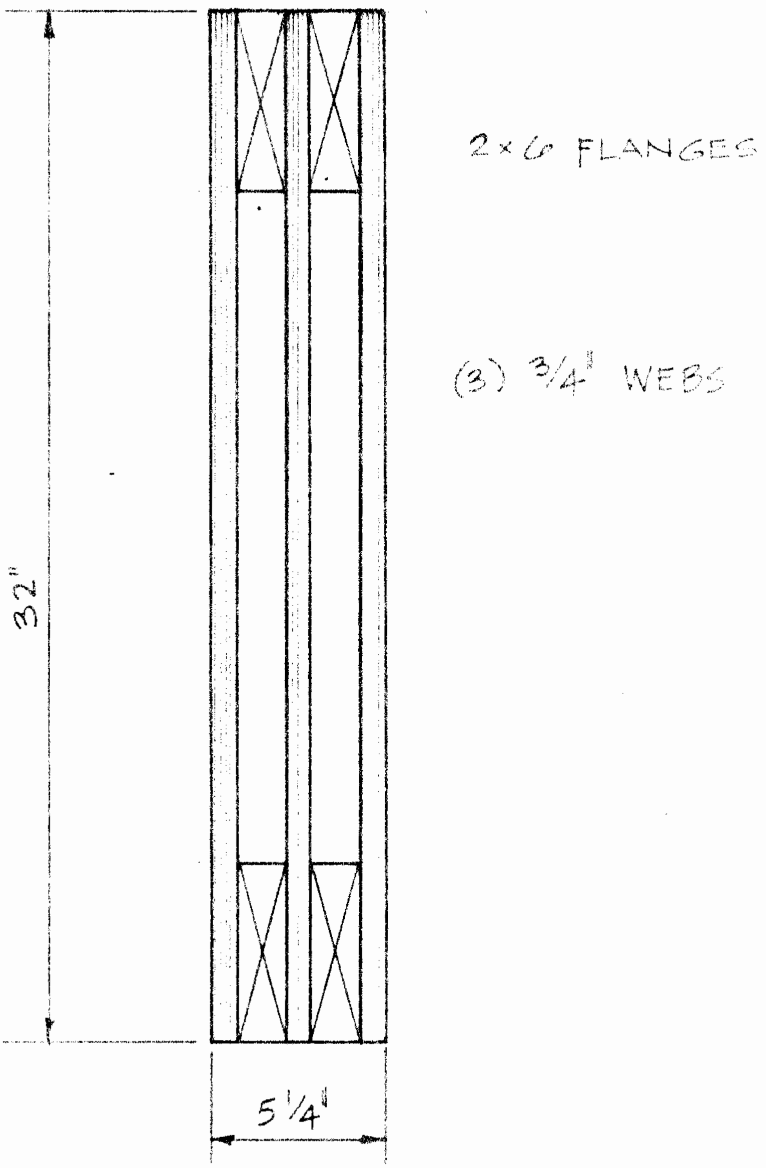


Figure 10

Sample Problem
Trial Section

shear stress. Following is gross moment of inertia for the sample problems's trial section.

2 x 6 flange, about axis through its own centroid (See figure 11 on page 33)

$$I = \frac{bd^3}{12} = \frac{(1.5)(5.5^3)}{12} = 20.8 \text{ inches}^4$$

Transferring this moment of inertia to the section's neutral axis: (See figure 12 on page 33)

$$I = I_o + Az^2 = 20.8 + (1.5)(5.5)(13.25^2) = 1469 \text{ inches}^4$$

Because there are four flanges: $\underline{X \quad 4}$

$$I_{(flanges)} = \underline{5876 \text{ in}^4}$$

3/4" plywood web, own axis coincides with section's N.A.

$$I = \frac{bd^3}{12} = \frac{(.75)(32^3)}{12} = 2084 \text{ in}^4$$

Because there are three Webs: $\underline{X \quad 3}$

$$\underline{6144 \text{ in}^4}$$

Gross moment of inertia (I_g):

$$I_g = I_f + I_{gw} = 5876 + 6144 = \boxed{12.020 \text{ in}^4}$$

The <u>net</u> moment of inertia, however, must be known in order to investigate the trial section's performance with respect to bending, shear, and deflection due to bending. The procedure is only slightly different from that of computing the gross moment of inertia. The moment of inertia of flanges remains exactly the same. The moment of inertia of the web members is calculated using only the effective thickness of the plywood webs. The effective thickness of a plywood web is the sum of the thicknesses of those plys having grain running in the same direction as the beam's longitudinal axis. The thickness of the plywood's crossbands is deducted from the total thickness. For 3/4 inch

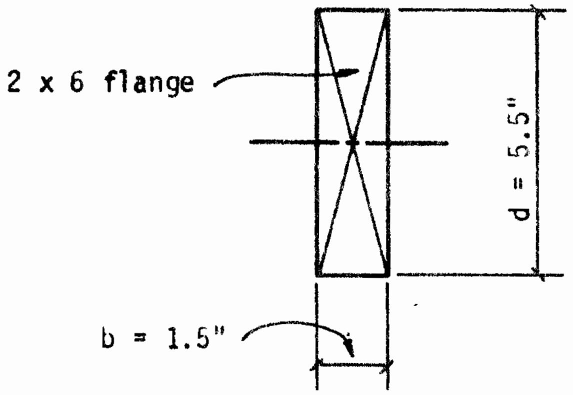


Figure 11

Sample Problem:
Flange Section

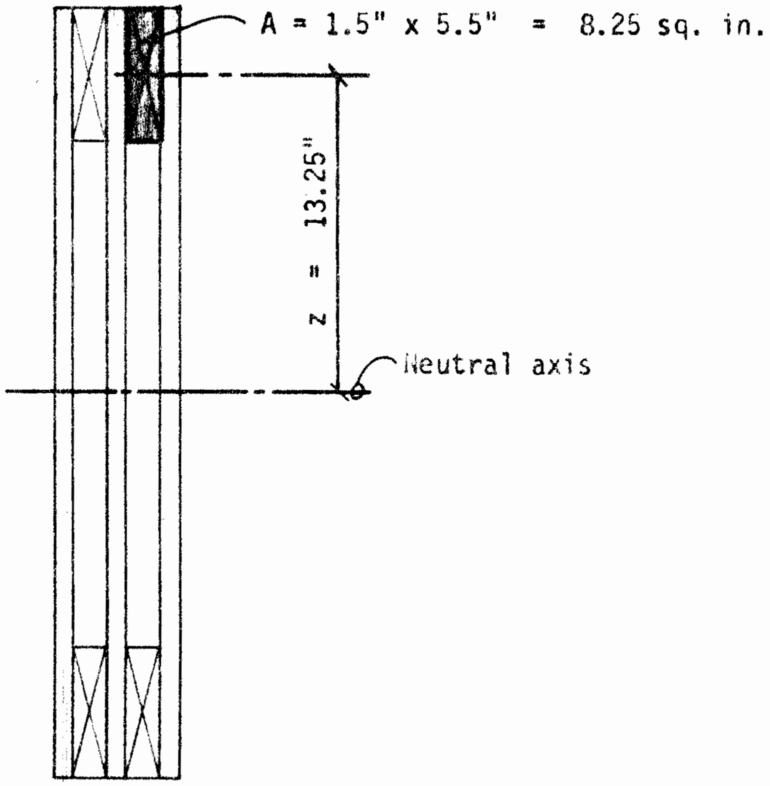


Figure 12

Sample Problem:
Transferring Flange Moment of Inertia

plywood, the effective thickness is determined thusly: (See appendix D, page 110)

$$\text{Faces: Two @ } 0.100'' = 0.200''$$

$$\text{Centers: One @ } 0.183'' = \underline{0.183''}$$

$$0.383'' \quad \text{(Effective web thickness)}$$

Therefore, the net moment of inertia of a web member is:

$$I_{ew} = \frac{bd^3}{12} = \frac{(.383)(32^3)}{12} = 1045 \text{ in}^4$$

$$\text{Because there are three webs: } \underline{\times \quad 3}$$

$$\underline{3135 \text{ in}^4}$$

Combining the net moment of inertia of the webs with the moment of inertia of the flanges:

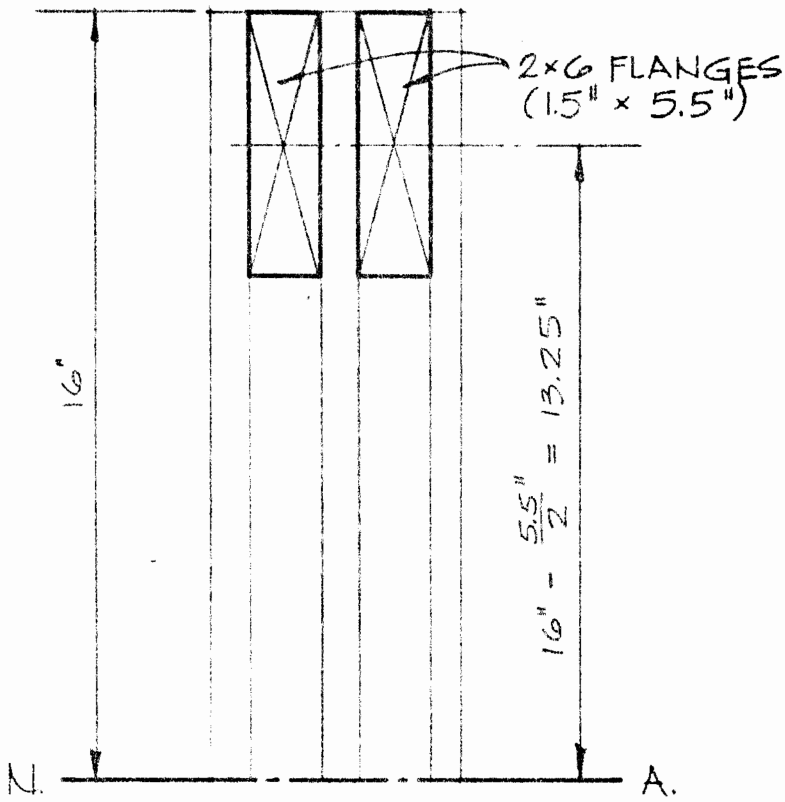
$$I_n = I_f + I_{ew} = 5876 + 3135 = \boxed{9011 \text{ in}^4}$$

The section modulus will be based on the net moment of inertia, as those web plys whose grain is vertical, do not contribute to the section's resistive moment. Therefore:

$$S = \frac{I}{c} = \frac{9011}{16} = \boxed{563 \text{ in}^3}$$

The designer must determine the trial section's statical moment. Actually there are two considerations here. The statical moment of the entire section will be used in investigating shear through-the-thickness (horizontal shear). The statical moment of just the flanges is used when investigating shear in the plane-of-plys (rolling shear stress) at glued, flange/web joints.

The statical moment of flanges for the sample problem is diagrammed and computed in figure 13 on page 35.



Q_f = moment of the cross-sectional area of the flanges, about the neutral axis.

$$Q_f = 2\left[(1.5)(5.5)(13.25)\right] = 219 \text{ in}^3$$

Figure 13

Sample Problem:
Solving for Q_f

The statical moment of the webs for the sample problem is diagrammed and computed in firgure 14 on page 37.

The statical moment of the entire section is equal to the sum of the statical moments of the parts. Therefore:

$$Q = Q_f + Q_w = 219 + 147 = \boxed{366 \text{ in}^3}$$

The last section property the designer needs to calculate is the weight. A close approximation of the section's weight can be made by assuming that the weight of wood is forty pounds per cubic foot. (this will err on the side of safety as most of the species commonly used in building construction will weigh a bit less than this.)

Therefore:

$$\text{Cross-sectional area} \times 1 \text{ foot} \times 40 \text{ \#/ft}^3 = \text{linear weight}$$

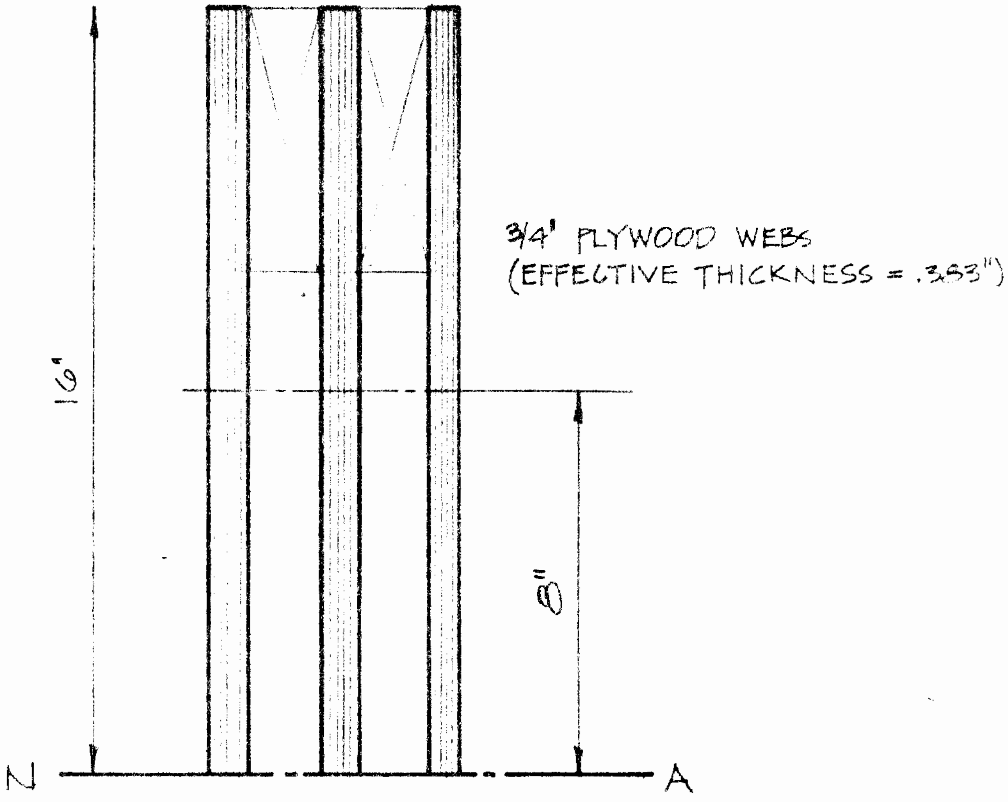
$$0.73 \text{ square feet} \times 1 \times 40 = \boxed{29 \text{ PLF}}$$

It may be helpful at this time to list all of the section properties that have been calculated for the sample problem.

Gross moment of inertia	I_g	= 12,020 in^4
Net moment of inertia	I_n	= 9,011 in^4
Section modulus	S	= 563 in^3
Statical moment	Q	= 366 in^3
Statical moment of flanges	Q_f	= 219 in^3
Weight	w	= 29 PLF

Bending Investigation

The flanges in a box beam largely determine the component's resistance to bending. Similar to simpy-supported steel wide-flanges and I-beams, the upper flanges are in compression and the lower flanges are in tension. So it is allowable tensile stresses and compressive



Q_w = Moment of the cross-sectional area of webs, about the neutral axis, considering only plys with grain parallel to the beam's longitudinal axis.

$$Q_w = 3\left[(16)(.383)(8)\right] = 147 \text{ in}^3$$

figure 14

Sample Problem:
Solving for Q_w

stresses, rather than allowable bending stresses that the designer is to consider when determining the moment resisting ability of the trial section. (A flange is actually subjected to some bending stress, however its magnitude is negligible.)

The allowable tensile stress of the lumber the researcher has chosen is 1200 PSI. This is less than the 1400 PSI allowable compressive stress, and therefore tension is the critical factor. With the section modulus and allowable stress known, the designer can compute the maximum allowable bending moment (resistive moment) for the trial section. For the sample problem:

$$M = f_t S = 1200 \text{ PSI} \times 563 \text{ in}^3 = \underline{675{,}000 \text{ in-lbs}}$$

The designer will now need to determine the actual bending moment created by the load:

Superimposed load + Beam weight = Total load

14,760 # + (29 PLF X 30 ft) = <u>15,630#</u>

The bending moment for a simply-supported beam having a uniformly distributed load is equal to:

$$M = \frac{Wl}{8} = \frac{(15{,}630)(360)}{8} = \underline{703{,}350 \text{ in-lbs}}.$$

In this case the actual bending exceeds the trial section's moment-resisting ability. The trial section must be altered.

The designer must make a decision. The physical size and/or shape of the trial section may be altered (section properties modified); or a different lumber species and/or grade may be used. The designer may alter the trial section by specifying larger flanges, additional flange members, deepen the section, additional webs, thicker webs, or any combination of these changes.

In this case, the researcher has decided to specify a "dense" grade of Select Structural Douglas Fir/Larch. Appendix C (page 105) lists the allowable tensile stress for this choice as 1400 PSI. Therefore the same-sized section now has the ability to resist a 17% greater bending moment.

$$M = f_tS = 1400 \text{ PSI} \times 563 \text{ in}^3 = \underline{788{,}200 \text{ in-lbs.}}$$

This new resistive moment exceeds the bending moment and therefore is deemed "acceptable" with respect to bending.

Shear Stress Investigation

Shear, through-the-thickness. Checking for excessive horizontal shear stress is an integral part of the design process for any wood flexural member. Allowable shear stress in solid wood is decidedly inferior when compare to its bending strength. Typically, wood shear strength is only 13% of its bending strength. (Hoyle, 1973, page 101) Shear forces are transmitted by the web members in box beams. This is similar to the web's function in rolled steel shapes. Because the web member in a box beam is plywood, the designer takes advantage of its superior shear strength (as compared to solid wood).

The allowable shear stress for the plywood specified in this sample problem (and all group one species of plywood) is 250 PSI. For solid wood this figure (F_v) would typically be less than 100 PSI (See appendix C, page 105-109). The total thickness of the plywood web is assumed to transmit the shear.

To compute the actual horizontal shear stress in the sample problem, the designer needs to solve the following equation.

$$f_v = \frac{V\,Q}{I_n \Sigma t_w}$$

Where:

f_v = actual horizontal shear stress

V = maximum vertical shear (15,630# ÷ 2 = 7815#)

I_n = net moment of inertia (9011 in^4)

Σt_w = sum of web thicknesses (3 X .75" = 2.25")

Q = statical moment (366 in^3)

For the sample problem:

$$f_v = \frac{V\,Q}{I_n \Sigma t_w} = \frac{(7815)(366)}{(9011)(2.25)} = \underline{141 \text{ PSI}}$$

Because this is considerably less than 250 PSI (the allowable), the designer concludes that the tial section section is acceptable with respect to horizontal shear.

Shear, in the plane-of-plys. When glue is used in the fabrication of the box beam, the designer shoudl be concerned with the stress developed at the junction of a flange and web. When comparing shear stress for lumber with the allowable shear in the plane-of-plys (rolling shear) of plywood, the plywood shear is the lesser of the two allowables_ and consequently is the critical element in this investigation. Robert Hoyle (1973, pages 65-66) presents a brief explanation of the concept of rolling shear.

> When plywood is loaded perpendicular to the panel faces, in flexure, the plies with grain perpendicular to the direction of span are the weakest aspect of the construction with respect to shear stress resistance. The wood fibers in these plies roll at stresses below the shear parallel-to-grain strength normally accorded solid lumber.

Excessive rolling shear therefore, could result in separation at the flange/web joint and effectively cause the component to fail.

The maximum allowable rolling shear stress, based on the researcher's assumption for the sample problem, is 75 PSI. In box beam construction however, this figure must be taken at 50% of the maximum (37.5 PSI) for the following reason. In reality, the load at such a connection creates shear stresses in the plywood that extend beyond the area of common surface on both sides. (Hoyle, 1973, page 66) The maximum value for rolling shear, given in the appendix relies on this phenomenon. In the case of the box beam, the plywood web extends past the flange on one side only, hence the fifty percent reduction in the allowable stress.

To compute the actual rolling shear stress at the flange/web joint, the designer must manipulate one of the two algebraic expressions given below.

For box beams with one "enclosed" web or two "non-enclosed" webs:

$$f_s = \frac{VQ_f}{2dI_n}$$

where: f_s = actual rolling shear stress
V = maximum vertical shear
d = flange depth
I_n = net moment of inertia
Q_f = statical moment of flanges

For box beams having more than one "enclosed" web or more than two webs, horizontal shear stress is not assumed to be equal in all webs. To facilitate calculations, flanges are divided into areas that are "tributary" to each web and then the rolling shear stress is computed for each flange/web joint. The flange area "served" by each web can be conveniently assigned by using the web thickness-to total-web thickness ratio, i.e. $t_w/\sum t_w$. (American Plywood Association, 1968, page 9)

For a box beam with one enclosed web, in which the thickness of the inner web is less than twice the thickness of an outer web, the maximum rolling shear stress will be present on the outside web. The magnitude can be calculated by the following formula:

$$f_s = \frac{VQ_f t_w}{dI_n \Sigma t_w}$$

Addressing the sample problem, the designer must solve the formula immediately above. Where:

$V = 7815$ #

$t_w = .75"$

$d = 5.5"$

$I_n = 9011 \text{ in}^4$

$t_w = 2.25"$

$Q_f = 219 \text{ in}^3$

Now, computing the rolling shear stress:

$$f_s = \frac{VQ_f t_w}{dI_n \Sigma t_w} = \frac{(7815)(219)(0.75)}{(5.5)(9011)(2.25)} = \underline{11.5 \text{ PSI}}$$

The actual rolling shear stress then, is well below our maximum allowable value of 37.5 PSI. The designer declares the trial section to be acceptable.

Deflection Investigation

The designer needs to control deflection of the member for structural and psychological reasons. Maximum deflection criteria are usually dictated by building codes. Commonly used maximums are 1/240th of span for total load deflection and 1/360th of span for live load deflection.

Approximate method. Plywood box beam deflections are typically computed by an approximate method. A more accurate method is used if deflection should prove critical using the approximate method.

By using the conventional beam deflection formulas (see appendix E, page 113), the designer can determine the deflection due to bending. Because these formulas ignore the deflection due to shear, the value found by the formula is then multiplied by the shear deflection factor from the chart below. This gives a close approximation of the total deflection.

Shear Deflection Factors	
Span/Depth Ratio	Factor
10	1.5
15	1.2
20	1.0

Figure 15

Table of Shear Deflection Factors

For the sample problem:

$$\Delta = \frac{5Wl^3}{384EI_n} = \frac{(5)(15,630)(360^3)}{(384)(1,800,000)(9011)} = .585''$$

The span/depth ratio is 360/32 = 11.25. By interpolating in the chart above, the shear deflection factor is 1.425. Therefore the approximate total deflection is: 1.425 X .585" = .833"

And since 1/240th of the sample problem's thirty foot span is 1.5", the deflection due to the total load is acceptable.

Considering only live load deflection:

Live load = 30 PSF X 360 ft^2 = 10,800#

$$\Delta = \frac{5Wl^3}{384EI_n} = \frac{(5)(10,800)(360^3)}{(384)(1,800,000)(9011)} = .405"$$

Adjusting, to include deflection due to shear:

1.425 X .405" = .577"

The maximum live load deflection cannot exceed 1/360th of the span, or one inch in this sample problem. Again, the deflection is quite acceptable.

Refined shear deflection. There is no need, in this example, to use a more refined method of calculating shear deflection as it is obviously not a critical factor with the trial section. The procedure however is presented, as follows. This method was developed by the American Plywood Association. The formula:

$$\Delta_s = \frac{PlKh^2C}{G\ I_g}$$

Where:

Δ_s = actual deflection due to shear

P = total load

l = span

h = depth of beam (see figure 16, page 45)

K = a factor, determined by the beam's cross section (see figure 17, page 46)

G = shearing modulus of the webs. (From tests, G may be taken as E/20 for panels with exterior glue. Where equilibrium moisture content in service will be 16% or higher, reduce this figure by 16%) (Tests by A.P.A.)

I_g = gross moment of inertia

C = coeficient, dependent on type of loading (See fig. 18 on page 47)

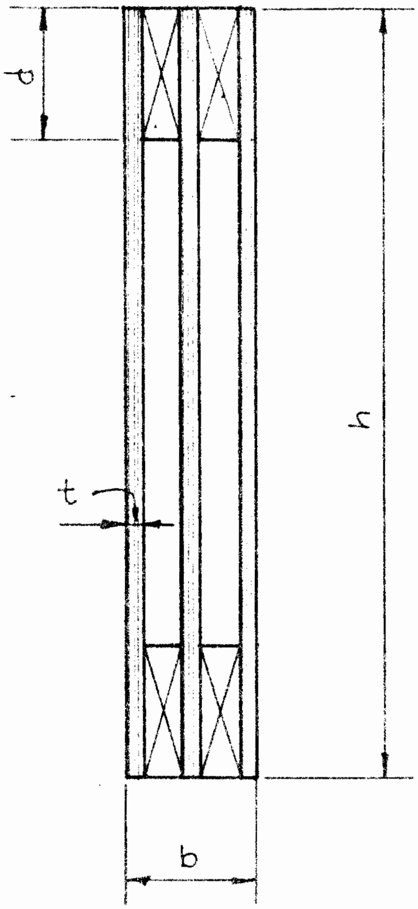


Figure 16

Shear Deflection Formula Variables

For built-up box beams that are symmetrical about both the vertical and horizontal axes (as is the case in most box beams), the value for "K" may be found by solving the equation below.

$$K = \frac{1}{4}\left[1 + \frac{12d^3 - 18hd^2 + 6h^2d}{h^3}\left(\frac{1}{\frac{\Sigma t}{b}} - 1\right)\right]$$

However, rather than "plug and chug" this rather lengthy formula, the American Plywood Association has developed the chart shown below.

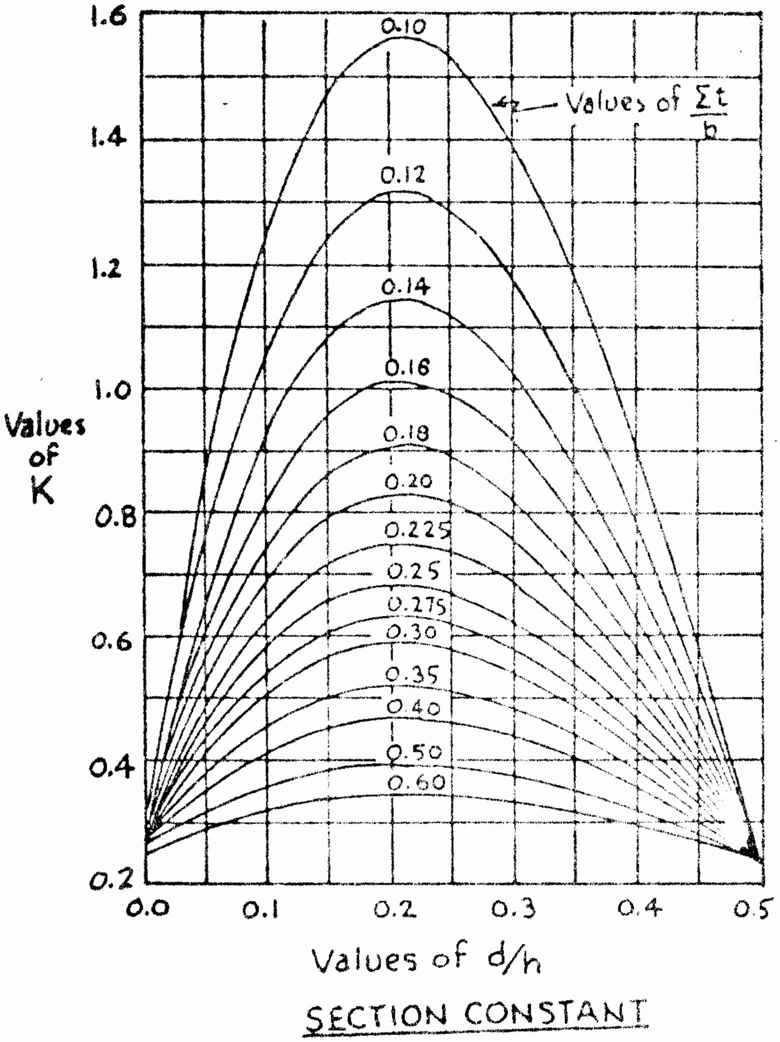


Figure 17

Shear Deflection Formula: K Factor

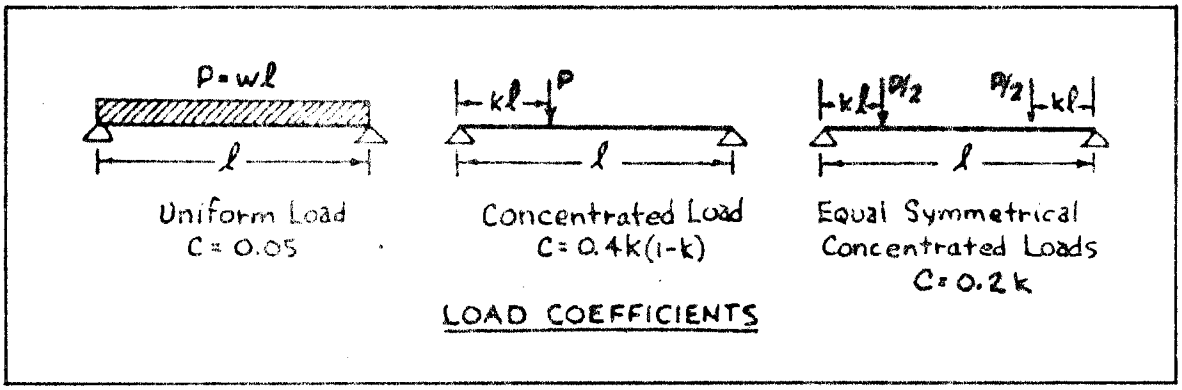


Figure 18

Shear Deflection Formula: C Factor
(American Plywood Association)

For the sample problem:

$P = 15{,}630\#$

$l = 360''$

$h = 32''$

$I_g = 12{,}020 \text{ in}^4$

$C = .05$

$G = 90{,}000$ PSI

$K = .44$

Solving for $_s$:

$$\Delta_s = \frac{PlKh^2C}{G\,I_g} = \frac{(15{,}630)(360)(.44)(32^2)(.05)}{(90{,}000)(12{,}020)} = .117''$$

Adding this figure to the deflection due to bending reveals total deflection. However, by using this more refined procedure, the modulus of elasticity for both the plywood and lumber may be increased by 10%. (Hoyle, 1973, page 248) Therefore:

$$\Delta = \frac{.585}{1.10} + .117 = .649''$$

The designer has now confirmed, with greater accuracy, that the trial section will not deflect excessively.

Web Stiffeners

Stiffeners, of dimension lumber, are required at the beam's reactions and at points of heavy concentrated loads (if any). They should fit snugly against top and bottom flanges and webs, and securely attached. (A.P.A., 1968, page 11)

For box beams with uniform loads, stiffeners should be placed at four foot intervals, or less, to prevent web buckling and increase resistance to horizontal shear stress. (Hoyle, 1973, page 248)

At reactions. Bearing stiffeners placed at reactions must be designed to meet both of the following criteria.

1. have sufficient cross section to bear the compressive load (Ibid.)
2. be large enough that the rolling shear stresses in the web/stiffener joint are not excessive. (Ibid.)

Typically, the stiffener should be as wide as the flange member. To determine their dimension parallel to the beam's longitudinal axis, consider the following: (A.P.A., 1968, pages 11-12)

For compressive strength (criterion #1):

$$x = \frac{P}{F_{c\perp}\Sigma b} \qquad \text{(Modification of the axial stress formula)}$$

Where: x = Thickness of stiffener

P = Concentrated load or reaction

$F_{c\perp}$ = Allowable stress in compression, perpendicular to the grain (for flange lumber)

Σb = Sum of flange widths above (or below) the neutral axis.

For the sample problem:

$$X = \frac{P}{F_{c\perp}\Sigma b} \qquad \frac{7815}{(455)(1.5)(2)} = 5.7''$$

For rolling shear stress (criterion #2): For box beams with one enclosed web or two non-enclosed webs, us the formula below. Box beams having more than two web members need not be investigated for rolling shear stress at stiffener/web joints, as it is unlikely to be a critical element. (A.P.A., 1968, page 11)

$$X = \frac{P}{2hF_s}$$

Where: h = beam depth

F_s = allowable rolling shear stress (With 50% reduction)

Uniformly distributed loads. For stiffeners not at beam ends, the fifty percent reduction factor of allowable rolling shear stress need not be taken. Also, in contrast to stiffeners at beam ends, the total load does not need to be transferred through the stiffener. A conservative estimate would be one-half. (Hoyle, 1973, page 249)

For beams with uniform loads, stiffeners are assumed to be four feet on center. This assumption is then investigated for adequacy. In the sample problem, the load on a four foot length of beam would be 2,084 pounds. One-half of this weight (1,042#) would be the "P" variable in the formulas given above.

Lateral Stability

Deep, narrow beams, although very efficient for resisting bending, may require restraint to prevent then from deflecting laterally. The American Plywood Association has issued the following guidelines for built-up plywood box beam lateral support. The table, on page 50, describes the type of restraint that is necessary, based on the section's depth/width ratio. (A.P.A., 1968, page 12)

Lateral Bracing Guidelines

Depth/Width Ratio:	Provision for Lateral Bracing:
Up to 5	None required
5 to 10	Ends held in position at bottom flange at supports.
10 to 20	Beam held in line at ends (both top and bottom flanges restrained from horizontal movement in planes perpendicular to beam's axis.)
20 to 30	One edge (either top or bottom) held in line.
30 to 40	Beam restrained by bridging or other bracing at intervals not more than eight feet.
more than 40	Compression flanges fully restrained and forced to deflect in a vertical plane, as with a well-fastened joist and sheathing or stressed-skin panel system.

Figure 19

Lateral Bracing Guidelines
(American Plywood Association)

Economy of Design

The structural integrity of the trial section has now been fully confirmed. The reader probably noticed that in some aspects of the design, the trial section was considerably more than adequate. The researcher, in presenting this sample problem, has not made an effort to maximize the economy of design. The designer may elect to revise the trial section in order to meet the structural needs of the application with a minimum of material and/or labor of fabrication. It is not the intent of the researcher to do so in this study.

It is obvious that this maximizing process could become a lengthy affair if economy were the main criterion. Equally obvious is the fact that the design process would be greatly facilitated through the use of a computer or programmable calculator. Each of the several steps in the design process could easily be written as a subroutine of the design program. Then the repetitious aspect of maximizing economy would require little time or effort on the part of the designer.

Chapter Five

INSTRUCTIONAL UNIT

This chapter contains instructional materials for presenting the built-up plywood box beam as a unit in a structural wood design course.

It is the opinion of the researcher that this unit should come after students have become familiar with design of flexural and axially loaded members of solid wood.

Following is an outline of the instructional materials in this chapter and suggestions for other teaching aids.

- I Student handouts
  - A. General unit information sheet.(see page 54)
  - B. Box beam general information handout

    Pages 55 through 65 are designed to serve as a student handout. That is the reason for dual pagination.) The handout gives general information about the box beam and consists of selected parts of chapters one, two and three of the study.
  - C. Box beam design handout

    Pages 66 through 86 are designed to serve as a student handout. It gives the design procedure, presented very nearly exactly as it appears in chapter four.
  - D. Unit examination (See page 87)
- II Instructional support
  - A. Audio-visual aids
    - 1. Overhead transparencies.

      The researcher suggests that transparencies be made from the figures in chapters one through four. These would prove particularly helpful in presenting the design procedure to the class.

2. Photographic slides of box beam applications

3. Mock-up of box beam sections

4. Field trip to see box beam fabrication and installation

5. If a testing lab is available, construct a small box beam and compare its structural performance with beams of solid wood having the same weight.

III Miscellaneous

A. Solution to unit examination (See pages 88-89)

B. Text book suggestion:

In researching the available materials and literature about the plywood box beam, the best reference found was Robert Hoyle's Wood Technology in the Design of Structures. This volume would make an excellant text, not only for box beam design, but for any course in structural wood design. The book that the researcher used was a 1973 edition. A new edition will be available very soon (April 1978) from the publishers: Mountain Press, 287 West Front Street; Missoula, Montana 59801. The tentative price is $12.50.

Hawkeye Institute of Technology

Architectural & Construction Drafting

Structural Wood Design

UNIT III: DESIGN OF BUILT-UP PLYWOOD BOX BEAMS

PURPOSE:

Present background information and procedures for the structural design of box beams.

PREREQUISITES:

Understanding of the fundamentals fo structural mechanics.

Knowledge of design of solid wood flexural members.

OBJECTIVE:

The student who successfully completes this unit will be able to design built-up plywood box beams for applications common to light frame construction.

TYPE OF INSTRUCTION:

Classroom discussion & demonstration, and student-solved problems.

REFERENCES:

Instructor prepared handouts.

Wood Technology in the Design of Structures
Robert Hoyle, Mountain Press, Missoula Montana

UNIT EVALUATION:

The student will be expected to demonstrate his/her knowledge and understanding by completing a performance based examination.

Grading criteria will consist of:

- Structural integrity of solution
- Accuracy and viability of assumption and computations
- Neat and logical format & Sketches
- Relative economy of design

Hawkeye Institute of Technology

Architectural & Construction Drafting

Structural Wood Design

BUILT-UP PLYWOOD BOX BEAMS: GENERAL INFORMATION

What is a built-up plywood box beam?

The built-up plywood box beam is a structural component using one or more webs of plywood with two or more flanges of lumber. The elements can be glued, nailed, or both, to form a monolithically-acting beam. The unit is hollow except for vertical lumber members placed at intervals to act as web stiffeners. (See figures A & B on following pages) The unit is similar to rolled steel sections in that the flanges resist bending while the web(s) transmit(s) shear forces. By using dimension lumber for the flanges and plywood for the webs, the structural properties of the two materials are used to their greatest efficiency. The result is an economical beam with a good weight-to strength ratio. The box beam is "particularly efficient where deep sections are desired for architectural effects." (American Plywood Association, 1965)

Uses and Advantages

> ...Plywood box beams are opening new horizons for building design each day. A highly versatile component spanning distances up to 120 feet, they utilize the structural soundness and inherent physical properties of plywood to achieve new and economical concepts. (Plywood Fabricator Service, 1959)

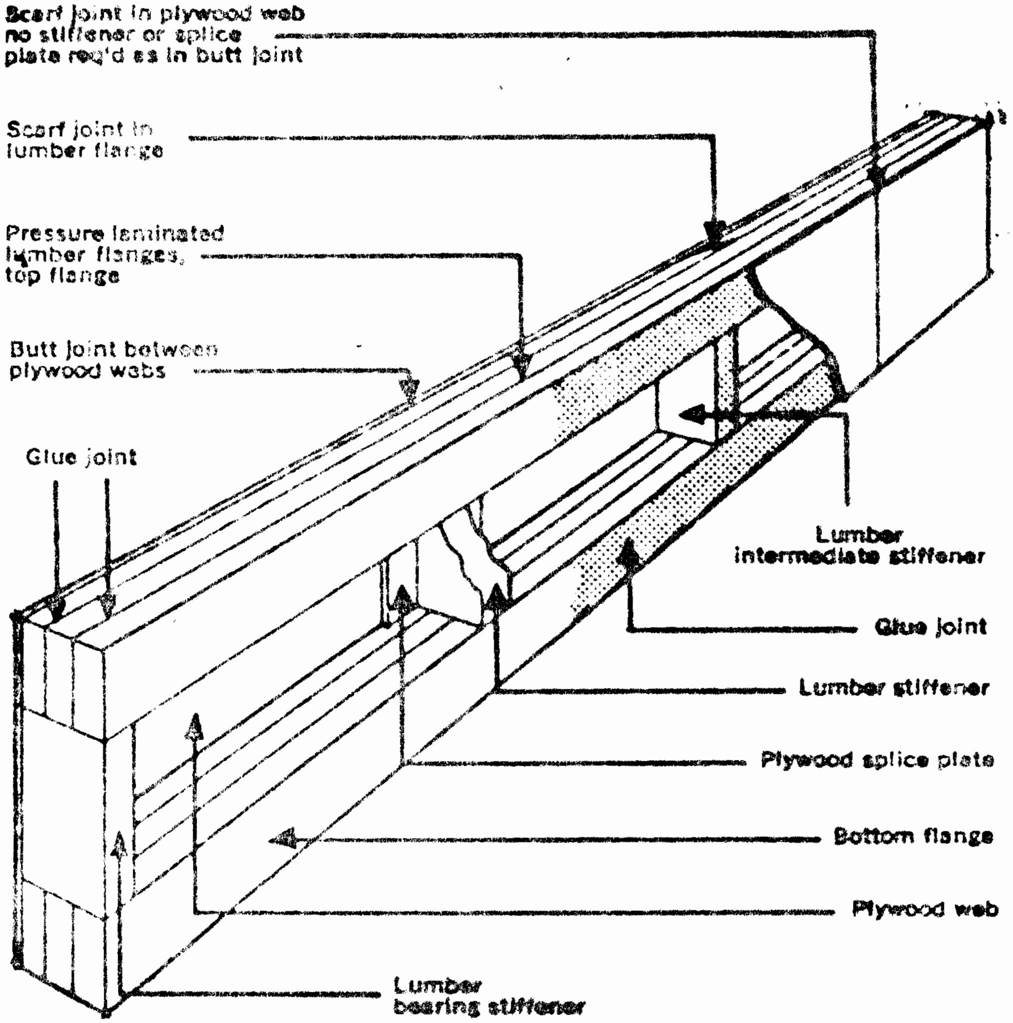


Figure A

Cut-away View of a Typical
Built-up Plywood Box Beam
(American Plywood Association)

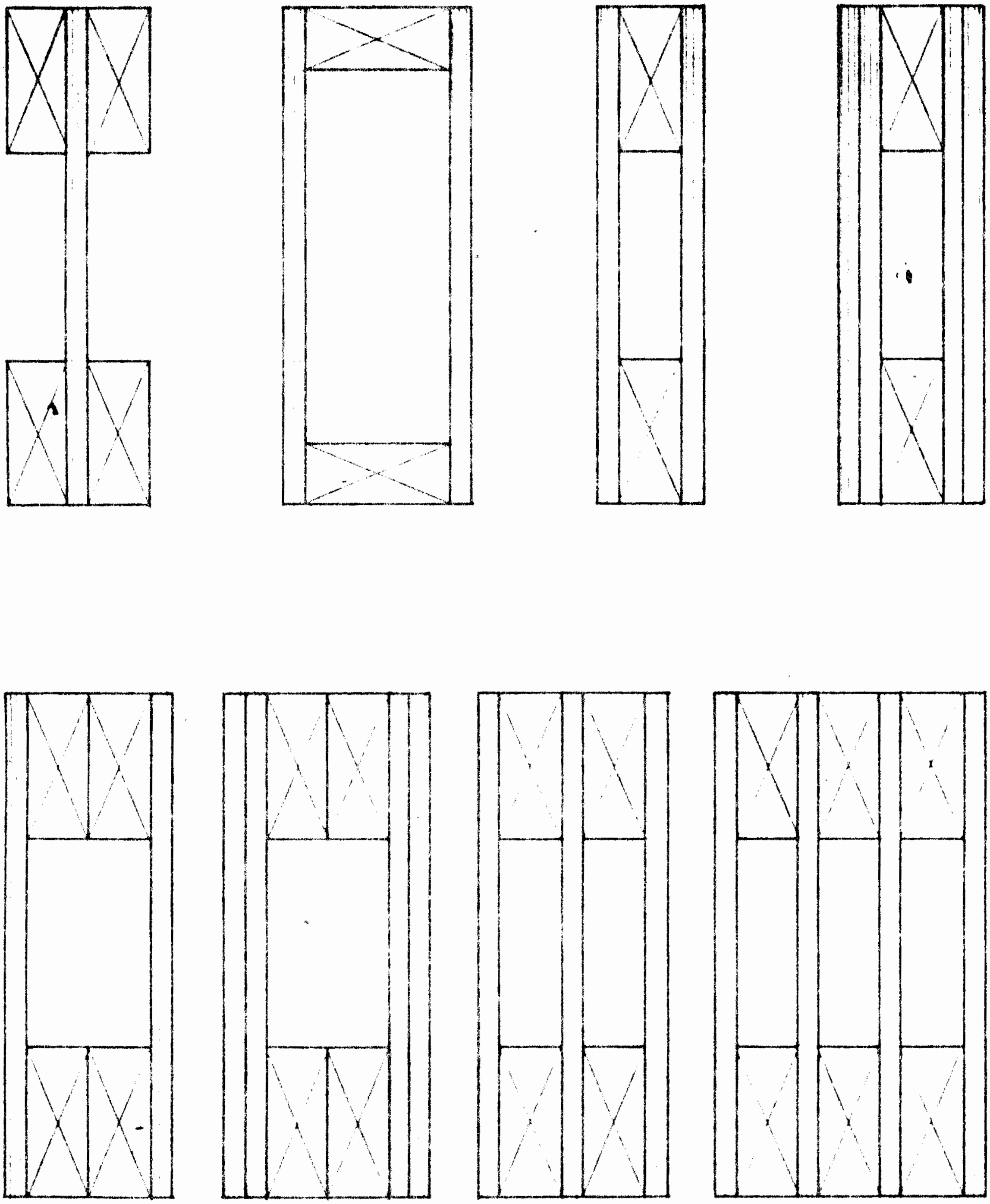


Figure 8

Typical Cross sections of
Built-up Plywood Box Beams

Plywood box beams have been used in almost every type of construction. Most often they find service as roof and floor beams, exposed rafters, lintels and ridge beams. However they have served as structural members for conveyor belts, pedestrian bridges and sign mountings. (DFPA, 1958, page 6) Weather does not restrict the usage of the box beam. They may be used in places of permanent exposure to extreme weather. With special treatment, they may be used where fire resistivity or decay is a concern.(Ibid.) Many of the problems of building maintenance encountered with solid wood members are prevented or minimized by using box beams. Seasoning defects and dimensional stability are but two examples. (Ibid.) Box beams can be built in various shapes, such as cambered, curved, arched or tapered, as well as the more conventional straight beam of rectangular cross section. (Perkins, 1962, page 90)

The Plywood Fabricator Service (1959) lists ten distinct advantages that the box beam has to offer.

* Great design freedom
* High strength and stiffness to weight ratios
* Rustproof and corrosion resistant
* Dimensional stability
* Freedom from large shrinkage cracks
* Smooth, easy to finish surfaces
* Reduced transportation costs
* Uniform manufacture
* Rapid delivery
* Low in-place costs

Fabrication

Box beams may be assembled using glue, nails, or a combination of both. Metal connectors may be used to laminate immediately adjacent flange members. Flanges may be placed either vertically or horizontally as shown in the figure below.

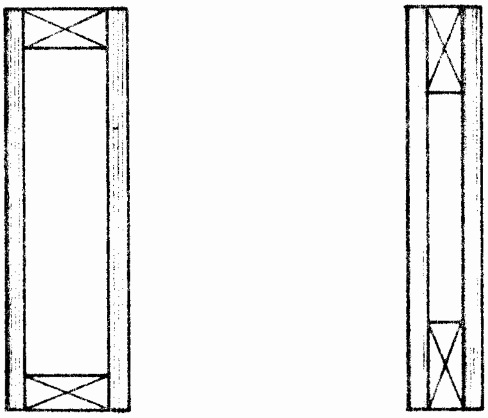


Figure C

Box Beam Cross Sections Showing
Vertical and Horizontal Flanges

Shop fabrication is recognized as the preferred construction practice. This permits full-pressure gluing. Although this requires expensive equipment, the resulting beam acts as a completely integral unit, with no slippage at joints or splices. This method also insures that stresses may be safely assumed up to the capacity of the plywood with respect to rolling shear. (Perkins, 1962, page 91)

Nail-gluing can yield satisfactory results also. However, if the beam is site-built, particular attention msut be placed on good gluing and nailing techniques, appropriate moisture content of the lumber and the like. (Ibid.) The design of nailed and glued members is the same as for glued only; the nailing is used to develop enough pressure to permit proper glue-line integrity.

The third recognized method of fabrication is nailing alone. This is the simplest and most economical method. Nail bearing strength is used to transmit shear stresses at web/flange joints. If shear stresses are moderate, as in most light frame construction applications, the system performs quite adequately. (Ibid.) Since no glue is used, rolling shear stress is not a design consideration; however the nail schedule is quite critical. (Moore, 1978) Nails having larger-than-normal heads and/or deformed shanks may be used to increase the bearing capacity of each nail, thereby permitting a wider nail spacing. (Perkins, 1962, page 91)

Figures D through H, on the pages following, illustrate the steps in fabricating and installing a built-up plywood box beam.

Engineered Plywood Components

Engineered plywood components are for the most part, prefabricated assemblies using one or more materials in conjunction with plywood. Their use has come about, partially, because of the significant increase in shop fabrication of building components. Typically these include stressed-skin panels, trussed rafters and joists, rigid frames, folded plates and box beams. (Perkins, 1962, page 75)

The use of components has had an effect on building construction in terms of economy and design. Erection time has been shortened while flexibility has increased. Most engineered plywood components use dimension lumber, glue and plywood; they have gained a rather wide acceptance. The several reasons for this include plywood's light weight along with

Figure D

Box Beam Fabrication:
Lumber Members Cut to Size,
Adjacent Flanges Laminated

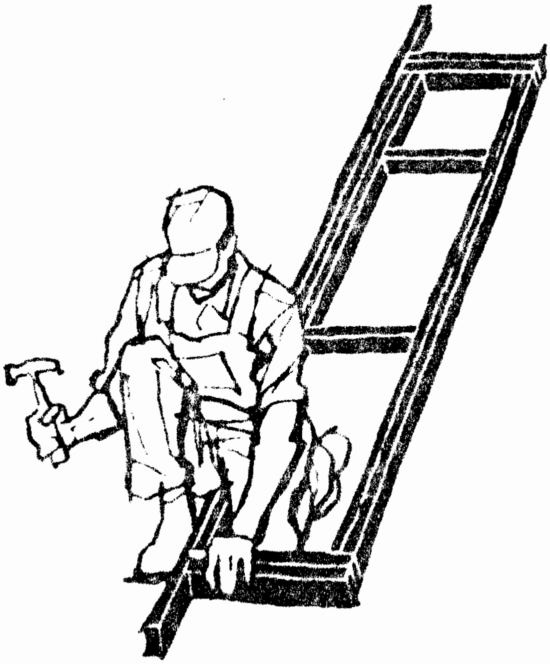


Figure E

Box Beam Fabrication:
Lumber Members Nailed or
nail-glued together

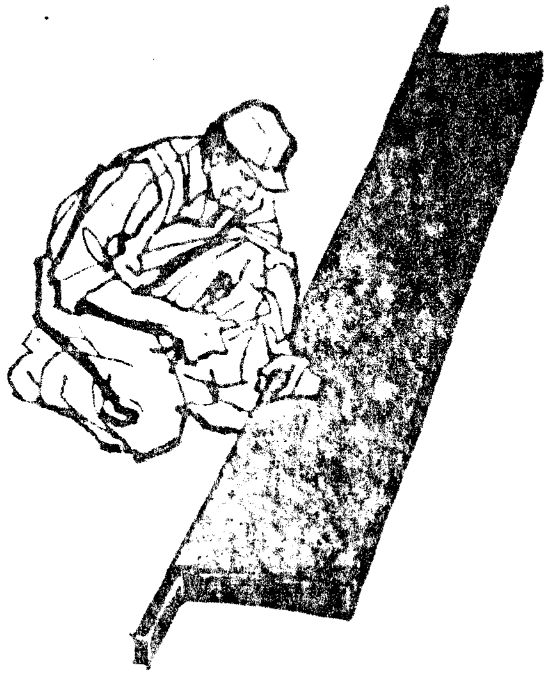


Figure F

Box Beam Fabrication:
Laminating Plywood Web
Members to Lumber Members

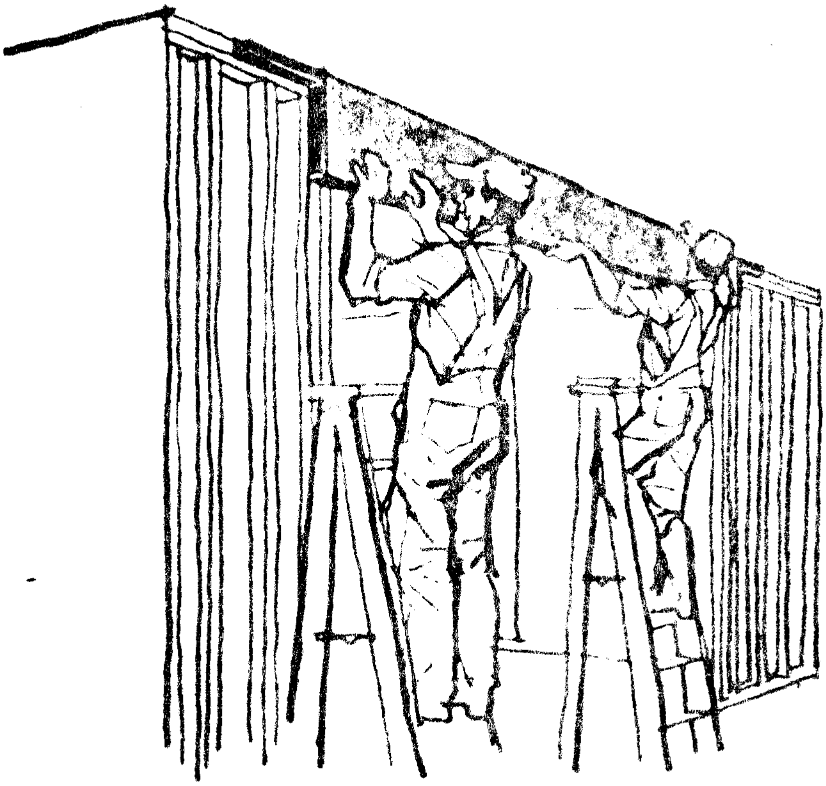


Figure G

Box Beam Fabrication:
Lifting Completed
Beam into Place

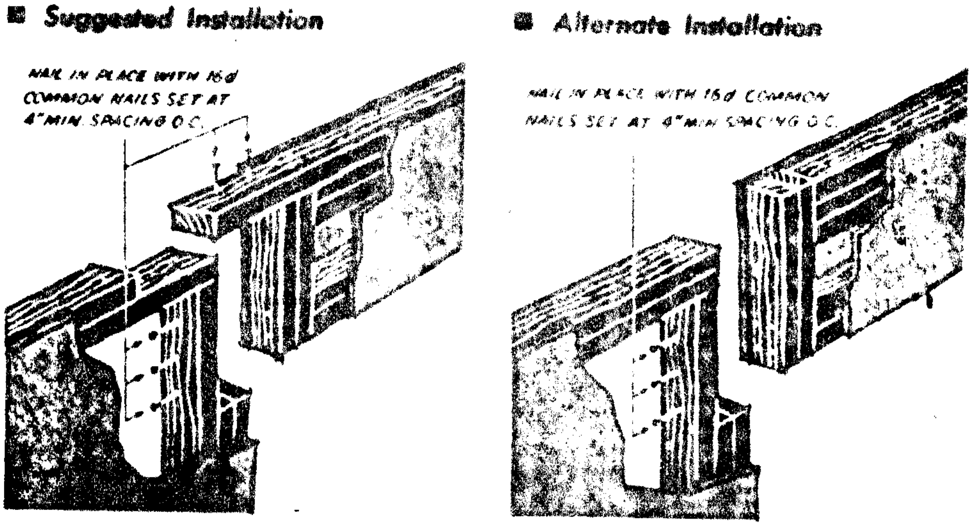


Figure H

Box Beam Fabrication:
Installation Details

the ease of fabrication and attachment to the other elements in wood construction. (Ibid.) Plywood components such as the box beam are now recognized by many of the model building codes. Waterloo and Cedar Falls have adopted the Uniform Building Code as published by the International Conference of Building Officials. Sections 2513 and 2514 of this code address the use of plywood components.

History

The historical front-runner of plywood components was the stressed-skin panel. (Vermilya, 1961, page 94) It was developed during the 1930's at the Forest Products Laboratory in Madison Wisconsin. The box beam was developed shorly after the stressed-skin panel, again largely due to the efforts of the Forest Products Lab. The concept of the box beam however, was used first in the United States for aircraft wing beams and struts in the 1920's. In fact the box beam research initially conducted at the FPL was done under the direction of the National Advisory Committee on Aeronautics. (Ibid. page 89)

One of the early publications dealing with the box beam is Section Nine of Technical Data Handbook, "Design of Built-up Beams with Plywood Webs" published in 1942 by the Douglas Fir Plywood Association. (Ibid.) Information about box beams also began to appear in periodicals about this same time. The March 1944 issue of Scientific American noted that box beams have advantages to offer the builder. The article stated that this "new product...has been developed by the Timbeam Company." An unsuccessful attempt was made to find out more about the Timbeam company, possibly the first to commercially construct the box beam.

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Hawkeye Institute of Technology
Architectural & Construction Drafting
Structural Wood Design

BUILT-UP PLYWOOD BOX BEAMS: STRUCTURAL DESIGN

Design Method

There are several references, texts, etc. which explain box beam design methods. May of the procedures are similar in that they are somewhat simplified, abbreviated or narrow in scope of application. The design method presented herein is the most accurate, comprehensive and up-to-date design procedure available.

Procedural Outline

The design procedure that will be followed in this handout can be outlined as follows.

I Loading
  A. Dead loads
  B. Live loads
  C. Type of loading
II Trial assumption
  A. Material specification
  B. Trial section
    1. Configuration
    2. Dimensions
    3. Section properties

a. Gross moment of inertia

b. Net moment of inertia

c. Section modulus

d. Statical moment

e. Weight per linear foot

III Bending investigation

A. Resistive moment

B. Bending moment

C. Modification of trial section

IV Shear stress investigation

A. Through-the-thickness (Horizontal shear)

B. At flange/web joints (Rolling shear)

V Deflection investigation

A. Approximate

1. Due to bending

2. Due to shear

B. Refined shear deflection

VI Web stiffeners

A. At reactions and concentrated loads

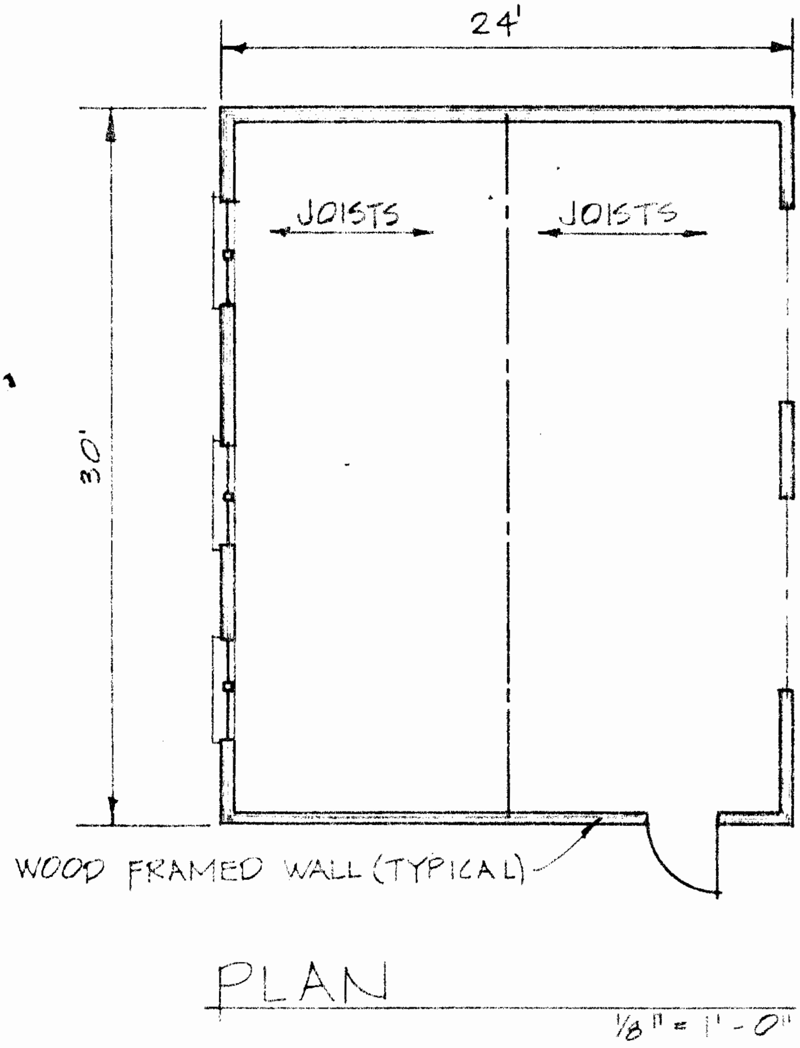
B. Uniformly distributed loads

VII Lateral stability

Sample Problem

Each of the items in the outline above will be explained by using the following sample problem.

The designer wishes to clear span the roof of the building shown in figure A (See page 3). The cost of transporting prefabricated roof



ROOF CONSTRUCTION:

3 PLY BUILT-UP ROOF
3/4" PLYWOOD DECK
2 × 10 JOISTS @ 2'-0" O.C.

Figure A

Sample Problem
Plan View of Building

trusses to the remote site would prove too costly; consequently, the decision has been made to place a job-built plywood box beam along the building's longitudinal axis. The beam will support roof joists which are placed at two foot intervals.

Loading

Recognizing that the beam in this application is a simply-supported member, having a uniformly distributed load, the designer will first need to determine the magnitude of the load. In this case, the dead loads consist of:

Built-up roofing	=	5.5 PSF
Plywood decking	=	2.0
Joists	=	3.5
		11.0 PSF

The live load will depend on local building codes. The designer should consult the appropriate code, or if none are in effect, select a live load from reference material, appropriate to the region. For purposes of this sample problem, thirty pounds per square foot will be used. Therefore: Total design load in PSF = 11 + 30 = 41 PSF.

In this typical application, the area of roof supported by the beam is equal to the beam span multiplied by the sum of half the joist span on both sides of the beam. For the sample problem, this area is equal to 30 feet X 12 feet, or 360 square feet.

Therefore, the total superimposed beam load is:

360 square feet X 41 PSF = 14,760#

Trial Assumption

The design process for box beams is to assume a member and then verify its structural integrity. This assumption has two main parts, selection of material to be used in the construction; and selection of a beam section (flange and web configuration, and depth).

Material specification. Materials must be specified for flange members and web members.

The dimension lumber used in the flanges may be specified in more than one manner. The designer may wish to call out species, grade, moisture content, etc. and use the design values assigned to his selection by the appropriate grading agency. The designer's selection should obviously be one that is available locally, at reasonable cost. An alternative to this method is for the designer to specify minimum values for bending, tension, compression, shear, modulus of elasticity, etc. without calling out a particular lumber species and grade.

Plywood is specified by calling out a particular grade and species group. Typically, plywood used in box beams are group one species of types having exterior glue.

For purposes of the sample problem, the following assumptions for material specifications are made:

Lumber: Douglas Fir/Larch, Select Structural Joists & Planks

Tension, parallel to grain (F_t) = 1,200 PSI

Compression, parallel to grain (F_c) = 1,400 PSI

Compression, perpendicular to grain ($F_{c\perp}$) = 455 PSI

Modulus of elasticity = 1,800,000 PSI

Plywood: Douglas Fir (Group 1), Structural I - AC

Tension, parallel to grain = 2,000 PSI

Compression, parallel or perpendicular to grain = 1,650 PSI

Shear, in the plane of plys (rolling) = 75 PSI

Shear, in plane perpendicular to plys = 250 PSI

Modulus of elasticity = 1,800,000 PSI

Trial section. There are tables that are designed to help the designer in making an assumption for the size and configuration of the trial section. However because of the virtually unlimited number of possible configurations, these tables are necessarily incomplete. The task of making this assumption becomes easier with experience. As with beams of steel or concrete, the deeper beam is usually the more economical choice. Plywood box beams are typically limited to four feet in depth, as commonly available plywood panels are four feet in width. There may be other considerations which dictate the physical dimensions of the beam section. Shown below is the trial section assumed for this sample problem.

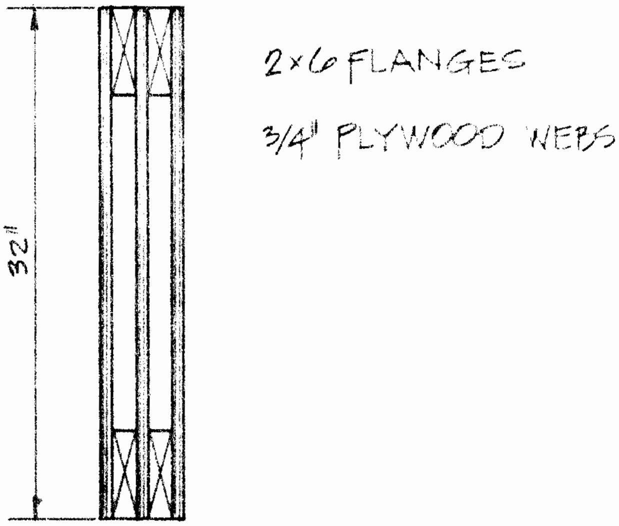


Figure B

Sample Problem
Trial Section

The next step is for the designer to calculate the structural properties of the trial section. This includes moment of inertia (both gross and net), section modulus, statical moments and section weight.

Computing the gross moment of inertia is accomplished exactly in the same manner as it is for any built-up section. The gross moment of inertia is needed when calculating the box beam's deflection due to shear stress. Follwing is the gross moment of inertia for the sample problem.

2x6 flange, about an axis through its own centroid: (see figure C, below)

$$I = \frac{bd^3}{12} = \frac{(1.5)(5.5^3)}{12} = \underline{20.8 \text{ in}^4}$$

Transferring this moment of inertia to the section's neutral axis: (See figure D, below)

$$I = I_0 + Az^2 = 20.8 + (1.5)(5.5)(13.25^2) = 1469 \text{ in}^4$$

Because there are four flanges: $\underline{X \quad 4}$

$$I_{(flanges)} = \underline{5876} \text{ in}^4$$

3/4" plywood, about own axis (which coincides with section's N.A.)

$$I = \frac{bd^3}{12} = \frac{(.75)(32^3)}{12} = 2084 \text{ in}^4; \text{ times 3 webs} = 6144 \text{ in}^4$$

Gross moment of inertia: $I_g = I_f + I_{gw} = 5876 + 6144 = \boxed{12{,}020 \text{ in}^4}$

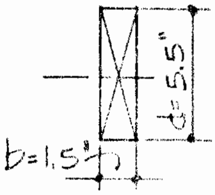


Figure C

Flange Section

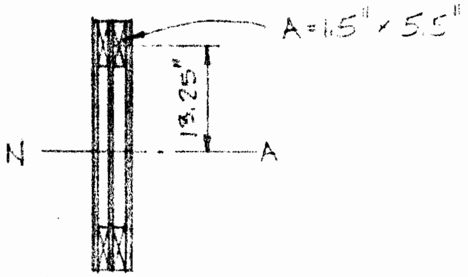


Figure D

Transferring Flange Moment of Inertia

The net moment of inertia, however, must be known in order to investigate the trial section's performance with respect to bending, shear, and deflection due to bending. The procedure is only slightly different from that of computing the gross moment of inertia. The moment of inertia of flanges remains exactly the same. The moment of inertia of the web members is calculated again, this time using only the effective thickness of the plywood webs. The effective thickness of a plywood web is the sum of the thicknesses of those plys having grain running in the same direction as the beam's longitudinal axis. The thickness of the plywood's crossbands is deducted from the total thickness. For 3/4 inch plywood, the effective thickness is determined thusly:

Faces: Two at 0.100" = 0.200 "

Centers: One at 0.183" $\underline{0.183}$ "

0.383" = t_{ew} (effective web thickness)

Therefore, the net moment of inertia of a web member is:

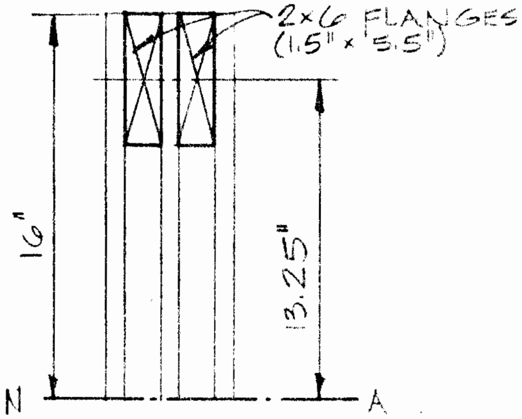
$$I = \frac{bd^3}{12} = \frac{(.383)(32^3)}{12} = 1045 \text{ in}^4, \text{ X } 3 \text{ webs} = \underline{3135 \text{ in}^4}$$

Combining the net moment of inertia of the webs with the moment of inertia of the flanges: $I_n = I_f + I_{ew} = 5876 + 3135 = \boxed{9011 \text{ in}^4}$

The section modulus will be based on the net moment of inertia, as those web plys whose grain is vertical do not contribute to the section's resistive moment. Therefore:

$$S = \frac{I}{c} = \frac{9011}{16} = \boxed{563 \text{ in}^3}$$

The designer must determine the trial section's statical moment. Actually there are two considerations here. The statical moment of the entire section will be used in investigating shear through-the-thickness (horizontal shear). The statical moment of just the flanges is used when investigating shear in the plane-of-plys (rolling shear) at glued, flange/web joints. See the figures below for diagrams and calculations for statical moments of webs and flanges.

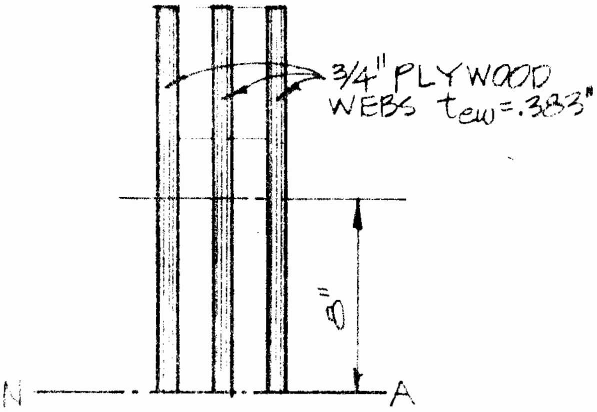


Q_f = moment of the cross section of the flanges, about the neutral axis.

$$Q_f = 2\left[(1.5)(5.5)(13.25)\right] = \boxed{219\ \text{in}^3}$$

Figure E

Solving for Q_f



Q_w = Moment of the cross section of webs, about the neutral axis, effective thickness of web only.

$$Q_w = 3\left[(16)(.383)(8)\right] = \boxed{147\ \text{in}^3}$$

Figure F

Solving for Q_w

The statical moment of the entire section is equal to the sum of the statical moments of the parts. Therefore:

$$Q = Q_f + Q_w = 219 + 147 = \boxed{366\ \text{in}^3}$$

The last section property the designer needs to calculate is the weight. A close approximation of the section's weight can be made by recalling that wood weighs forty pounds per cubic foot. (This will err on the side of safety as most of the species commonly used in building construction will weight a bit less than this.) The cross-sectional area of the section being considered is 0.73 square feet. Therefore it will weigh approximately 29 pounds per linear foot.

It may be helpful at this time to list all of the section properties that have been computed for the sample problem's trial section.

Gross moment of inertia	I_g	=	12,020 in^4
Net moment of inertia	I_n	=	9,011 in^4
Section modulus	S	=	563 in^3
Statical moment	Q	=	366 in^3
Statical moment of flanges	Q_f	=	219 in^3
Weight	w	=	29 PLF

Bending Investigation

The flanges in a box beam largely determine the component's resistance to bending. Similar to simply-supported steel wide-flanges and I-beams, the upper flanges are in compression and the lower flanges are in tension. So it is allowable tensile stresses and compressive stresses, rather than allowable bending stresses that the designer is to consider when determining the moment resisting ability of the trial section. (A flange is actually subjected to some bending stress, however its magnitude is negligible when compared to direct stress.)

The allowable tensile stress of the lumber the researcher has chosen is 1200 PSI. This is less than the 1400 PSI allowable compressive stress, and therefore tension is the critical design value in bending. With the section modulus and allowable stress known, the designer can compute the maximum allowable bending moment (resistive moment) for the trial section. For the sample problem:

$$M = F_tS = 1200 \text{ PSI} \times 563 \text{ in}^3 = \underline{675{,}000 \text{ in-lbs.}}$$

The designer will now need to determine the actual bending moment created by the load:

Superimposed load + Beam weight = Total load

$$14{,}760\# + (29 \text{ PLF} \times 30 \text{ ft}) = \underline{15{,}630\#}$$

The bending moment for a simply-supported beam having a uniformly distributed load is equal to:

$$M = \frac{Wl}{8} = \frac{(15{,}630)(360)}{8} = \underline{703{,}350 \text{ in-lbs.}}$$

In this case the actual bending moment exceeds the trial section's moment resisting ability. The trial section must be altered.

The designer must make a decision. The physical size and/or shape of the trial section may be altered (section properties modified) or a different lumber species and/or grade may be used. The designer may alter the trial section by specifying larger flanges, additional flanges, deepen the section, additional webs, thicker webs, or any combination of these changes.

In this case, the decision has been made to specify a "dense" grade of Select Structural Douglas Fir/Larch. The allowable tensile stress for this choice is 1400 PSI. This change results in a 17%

increase in resistive moment, without increasing the size or weight of the trial section.

$$M = F_t S = 1400 \text{ PSI} \times 563 \text{ in}^3 = \underline{788{,}200 \text{ in-lbs}}$$

This new resistive moment exceeds the bending moment and therefore is deemed "acceptable" with respect to bending.

Shear Stress Investigation

Shear, through-the-thickness. Checking for excessive horizontal shear stress is an integral part of the design process for any wood flexural member. Allowable shear stress in solid wood is decidely inferior when compared to its allowable bending strength. Typically, wood shear strength is only 13% of its bending strength. (Hoyle, 1973, page 101) Shear forces are transmitted by the web members in box beams. This is similar to the web's function in rolled steel shapes. Because the web member in a box beam is plywood, the designer takes advantage of its superior shear strength (as compared to solid wood).

The allowable shear stress for the plywood in this sample problem (and for all group one species of plywood) is 250 PSI. For solid wood this figure would typically be less than 100 PSI. The total web thickness is assumed to transmit the shear.

To compute the actual horizontal shear stress in the sample problem, the designer needs to solve the following equation.

$$f_v = \frac{V\,Q}{I_n \Sigma t_w}$$

Where: f_v = actual horizontal shear stress

V = Maximum vertical shear

I_n = net moment of inertia

Σt_w = sum of web thicknesses

Q = statical moment

For the sample problem:

$$f_v = \frac{V\,Q}{I_n \Sigma t_w} = \frac{(7815)(366)}{(9011)(2.25)} = \underline{141 \text{ PSI}}$$

Because this is less than the 250 PSI allowable stress, the designer concludes that the trial section is acceptable with respect to horizontal shear.

Shear, in the plane-of-plys. When glue is used in the fabrication of the box beam, the desin-er should be concerned with the stress developed at the junction of a flange and web. When comparing shear stress for lumber with the allowable shear in the plane-of-plys (rolling shear) of plywood, the plywood shear is the lesser of the two and consequently is the critical element in this investigation. Robert Hoyle (1973, pages 65-66) presents a brief explanation of the concept of rolling shear.

> When plywood is loaded perpendicular to the panel faces, in flexure, the plies with grain perpendicular to the direction of span are the weakest aspect of the construction with respect to shear stress resistance. The wood fibers in these plies roll at stresses below the shear parallel-to-grain strength normally accorded solid wood.

Excessive rolling shear therefore, could result in separation at the flange/web joint and effectively cause the component to fail.

The maximum allowable rolling shear stress, based on the assumption made earlier for the sample problem, is 75 PSI. In box beam construction however, this figure must be reduced by 50% for the following reason. In reality, the load at such a connection creates shear stresses in the plywood that extends beyond the area of common surface on both sides. (Hoyle, 1973, page 66) The maximum value given in tables for this rolling shear relies on this phenomenon. In the case of the box beam, the plywood web extends past the flange on one side only, hence the fifty percent reduction in the allowable stress.

To compute the actual rolling shear stress at the flange/web joint, the designer must manipulate one of the two equations below.

For box beams with one enclosed web or two non-enclosed webs:

$$f_s = \frac{VQ_f}{2dI_n}$$

where: f_s = actual rolling shear stress
V = maximum vertical shear
d = flange depth
I_n = net moment of inertia
Q_f = statical moment of flanges

For box beams having more than one enclosed web or more than two webs, horizontal shear stress is not assumed to be equal in all webs. To facilitate calculations, flanges are divided into areas that are "tributary" to each web and then the rolling shear stress is computed for each flange web joint. The flange area "served" by each web can be conveniently assigned by using the web thickness-to-total-web thickness ratio, i.e. $t_w/\Sigma t_w$. (American Plywood Association, 1968, page 9)

For a box beam with one enclosed web, in which the thickness of the inner web is less than twice the thickness of an outer web, the maximum shear stress will be present on the outside web. The magnitude of that stress can be calculated by the following formula:

$$f_s = \frac{VQ_f t_w}{dI_n \Sigma t_w} = \frac{(7815)(219)(0.75)}{(5.5)(9011)(2.25)} = \underline{11.5 \text{ PSI}}$$

The actual rolling shear stress in our sample problem is well below the maximum allowable value of 37.5 PSI.

Deflection Investigation

Just as in solid wood beam design, the amount of deflection must be controlled. Many building codes specify a maximum deflection of span/240 for total loads and span/360 for live loads only.

Approximate method. Plywood box beam deflections are typically computed by an approximate method. A more accurate method is used if deflection should prove critical when using the approximate method.

By using the conventional beam deflection formulas, the designer can determine the deflection due-to-bending. Because these formulas ignore the deflection due-to-shear, the value found by the formula is then multiplied by the shear deflection factor from the chart below. This gives a close approximation of the total deflection.

Shear Deflection Factors	
Span/Depth Ratio	Factor
10	1.5
15	1.2
20	1.0

Note: Span/depth ratios larger than 20 need not be considered to add any deflection due-to-shear. The designer may interpolate in the chart but is cautioned against extrapolating data for ratios less than ten. See the refined method for shear deflection.

Since dead loads in light frame construction are relatively small when compared to live loads, live load deflections are generally the more restrictive. For this reason, only live load deflection will be computed for the sample problem.

Live load = 30 PSF X 360 ft^2 = 10,800#

$$\Delta = \frac{5Wl^3}{384\ EI_n} = \frac{(5)(10{,}800)(360^3)}{(384)(1{,}800{,}000)(9011)} = \underline{.405"}$$

The span depth ratio for the sample problem is 360/32, or 11.25. By interpolating in the chart of shear deflection factors, we find that a factor of 1.425 will approximate the total deflection due-to-live load. Therefore: 1.425 X .405" = <u>.577"</u> . Since the allowable deflection is equal to the span/360, or one inch in this case, the total actual deflection is quite acceptable.

<u>Refined shear deflection</u> The following presentation was developed by the American Plywood Association and yields shear deflections that are more accurate than the previous discussion. This refined method uses empirical data derived from testing done by A.P.A.

The formula:

$$\Delta_s = \frac{PlKh^2C}{G\ I_g}$$

Where: Δ_s = actual deflection, due-to-shear

P = total load

l = span

h = depth of section

K = a factor, determined by the beam's cross section. (See figure G, page 82)

G = shearing modulus of the webs. (from tests, G may be taken as E/20 for panels with exterior glue. Where equilibrium moisture content in service will be 16% or higher, reduce this figure by 16%.) (Tests by A.P.A.)

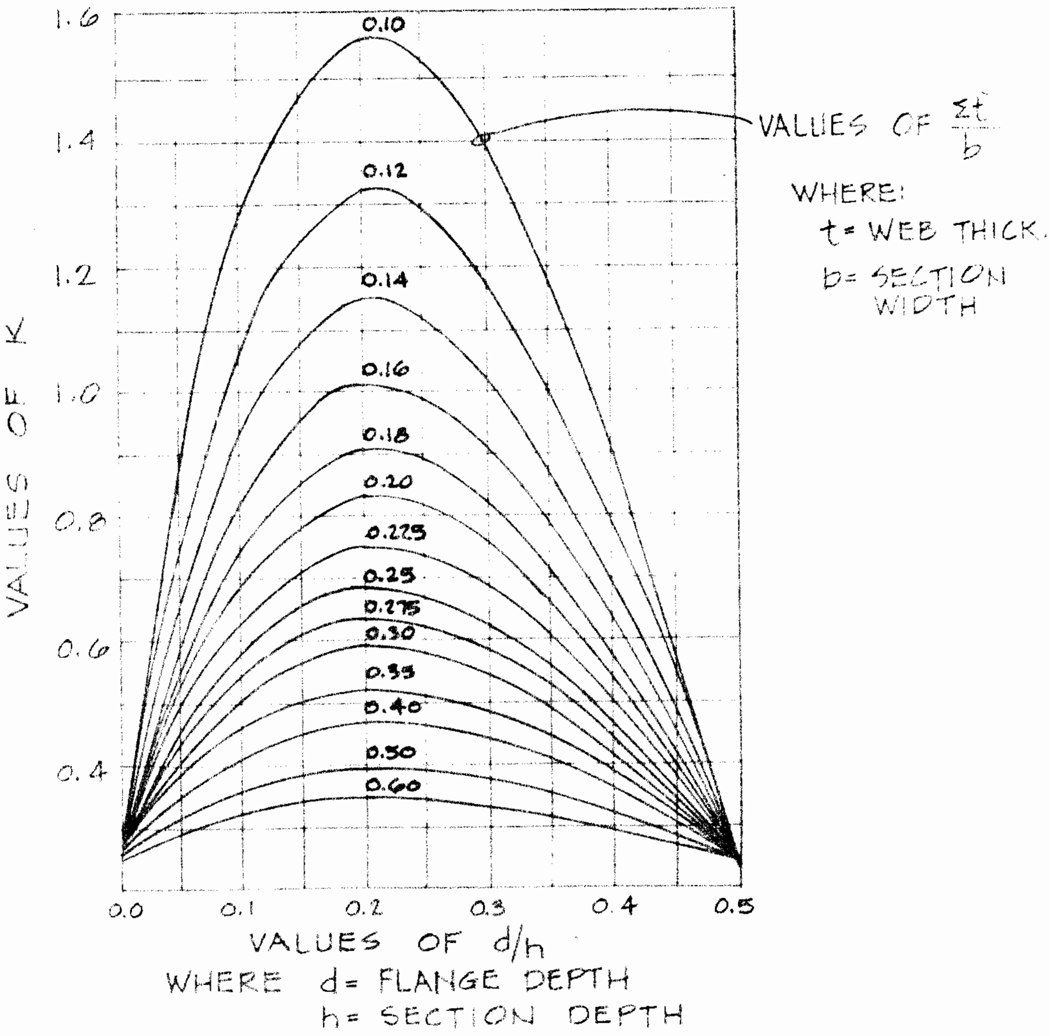
I_g = <u>gross</u> moment of inertia

C = coefficient, dependent on type of loading. (See figure H, page 83)

For built-up box beams that are symmetrical about both the vertical and horizontal axes (as in the case of most box beams), the value for "K" may be found by solving the equation below.

$$K = 1/4 \quad 1 + \frac{12d^3 - 18hd^2 + 6h^2d}{h^3} \; \frac{1}{\frac{\Sigma t}{b}} - 1$$

However, rather than "plug and chug" this rather lengthy formula, the American Plywood Association has developed the chart shown below.



Shear Deflection Formula: K Factor

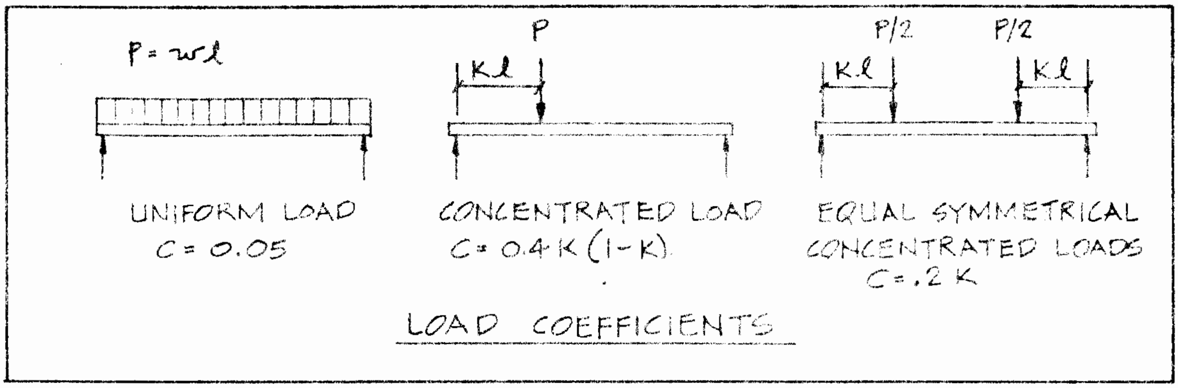


Figure H

Shear Deflection Formula: C Factor
(American Plywood Association)

For the sample problem:

$P = 10{,}800\#$ $\qquad C = .05$

$l = 360''$ $\qquad G = 90{,}000$ PSI

$h = 32''$ $\qquad K = .44$

$I_g = 12{,}020 \text{ in}^4$

Solving for Δ_s:

$$\Delta_s = \frac{Plkh^2C}{G\ I_g} = \frac{(10{,}800)(360)(.44)(32^2)(.05)}{(90{,}000)(12{,}020)} = .117''$$

Adding this figure to the deflection due-to-bending reveals the total deflection. However, since we used the refined method for calculating, the elastic modulus of the lumber and plywood may be increased by ten percent. (Hoyle, 1973, page 248) Therefore:

$$\Delta = \frac{.405}{1.10} + .081 = .449''$$

The designer has now confirmed, with greater accuracy, that the trial section will not deflect excessively.

Web Stiffeners

Stiffeners, of dimension lumber, are required at the beam's reactions and at points of heavy concentrated loads (if any). They should fit snugly against top and bottom flanges and webs, and securely attached. (A.P.A., 1968, page 11)

For box beams with uniform loads, stiffeners should be placed at four foot intervals, or less, to prevent web buckling and increase the beam's resistance to horizontal shear stress. (Hoyle, 1973, page 248)

At reactions. Bearing stiffeners placed at reactions must be designed to meet both of the following criteria:

1. have sufficient cross section to bear the compressive load. (Ibid.)
2. be large enough that the rolling shear stresses in the web/stiffener joint are not excessive. (Ibid.)

Typically, the stiffener should be as wide as the flange member. To determine their dimension parallel to the beam's longitudinal axis, consider the following formula. (A.P.A., 1968, pages 11-12) The formula is a modification of the axial stress formula.

For compressive strength (criterion #1):

$$x = \frac{P}{F_{c\perp} \sum b}$$

Where: x = thickness of stiffener

P = Concentrated load or reaction

$F_{c\perp}$ = allowable stress in compression, perpendicular to the grain of flange lumber

$\sum b$ = Sum of flange widths above (or below) the neutral axis.

For the sample problem:

$$X = \frac{P}{F_c \ b} = \frac{7815}{(455)(1.5)(2)} = 5.7''$$

For rolling shear stress (Criterion #2): For box beams with one enclosed web or two non-enclosed webs, us the formula below. Box beams having more than two web members need not be investigated for rolling shear stresses at stiffener/web joints, as it is unlikely to be a critical element. (A.P.A., 1968, page 11)

$$X = \frac{P}{2hF_s}$$

where: h = beam depth

F_s = allowable rolling shear stress (with fifty percent reduction)

Uniformly distributed loads. For stiffeners not at beam ends, the fifty percent reduction factor of allowable rolling shear stress need not be taken. Also, in contrast to stiffeners at beam ends, the total load does not need to be transferred through the stiffener. A conservative estimate would be one-half. (Hoyle, 1973, page 249)

For beams with uniform loads, stiffeners are assumed to be four feet on center. This assumption is then investigated for adequacy. In the sample problem, the load on a four foot length of beam would be 2,084#. One half of this weight (1,042#) would be the "P" variable in the formulas given above.

Lateral Stability

Deep, narrow beams, although very efficient for resisting bending, may require restraint to prevent them from deflecting laterally. The American Plywood Association has issued the following guidelines for built-up plywood box beam lateral support. (A.P.A., 1968, page 12)

Lateral Bracing Guidelines (American Plywood Association)	
Depth/Width Ratio	Provisions for lateral support
Up to 5	None required
5 to 10	Ends held in position at bottom flange at supports
10 to 20	Beam held in line at ends (both top and bottom flanges restrained from horizontal movement in planes perpendicular to beam's axis)
20 to 30	One edge (either top or bottom) held in line.
30 to 40	Beam restrained by bridging or other bracing at intervals not more than eight feet.
more than 40	Compression flanges fully restrained and forced to deflect in a vertical plane, as with a well-fastened joist and sheathing or stressed-skin panel system.

Economy of Design

The structural integrity of the trial section has now been fully investigated and confirmed. The reader probably noticed that in some aspects of the design, the trial section was considerably more than just adequate. No attempt was made to maximize the economy of design. The designer may elect to revise the trial section in order to meet the structural needs of the application with a minimum of material and/or labor of fabrication.

References Cited:

Design of Plywood Beams, American Plywood Association, 1968.

Hoyle, R.J. Wood Technology in the Design of Structures, Missoula, Montana: Mountain Press Publishing Company, 1973.

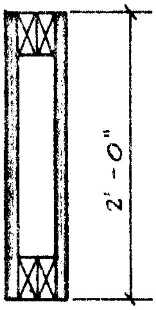
Hawkeye Institute of Technology

Architectural & Construction Drafting

Structural Wood Design

UNIT III EXAMINATION

Investigate the structural integrity of the trial section in figure 1. The box beam will be used as a header over an opening in the load bearing wall as shown in figure 2.



Flanges are 2x4 (1.5" x 3.5") of Dense Select Structural Southern Pine, K.D. 15% MC

Webs are 3/4" thick plywood panels of Structural I A-C type plywood.

NOTE: The design of web stiffeners need not be done for this examination.

Figure #1: Trial section and Material Specification

Roof construction = 10 PSF

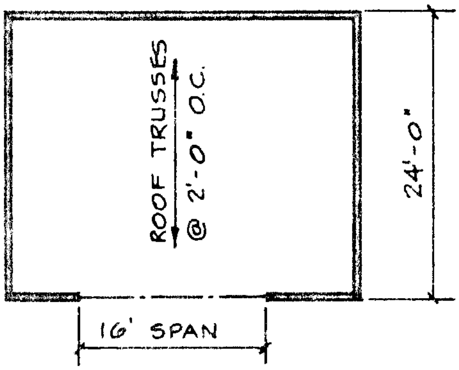


Figure #2: Plan view of Building

You may use references to aid you in the completion of this exam.

Your solution should be presented in a neat, logical and orderly format.

Show your work, except arithmetic, using labels and proper units of measure. Sketches may help to explain your work.

Write down any algebraic formulas before you plug in values for the variables.

UNIT III EXAM.

PAGE 1 OF 2

LOADING

DEAD LOAD (GIVEN) = 10 PSF
LIVE LOAD (ASSUMED) = 30 PSF
40 PSF

ROOF AREA SUPPORTED: 16' × 12' = 192 □
SUPERIMPOSED LOAD = 7680 #

TRIAL SECTION PROPERTIES

MOMENT OF INERTIA

2x4 FLANGE:

$$I = \frac{bd^3}{12} = \frac{1.5 \times 3.5^3}{12} = 5.36 \text{ IN}^4$$

TRANSFER:

$$I = I_o + Az^2 = 5.36 + (1.5 \times 3.5)(10.25^2) = 557 \text{ IN}^4$$

× 4 FL.

2228 IN^4

WEB (NET):

EFFECTIVE THICKNESS (FROM TABLES) = .383

$$I = \frac{bd^3}{12} = \frac{.383 \times 24^3}{12} = 441 \text{ IN}^4 \times 2 \text{ WEBS} = 882 \text{ IN}^4$$

WEB (GROSS):

$$I = \frac{bd^3}{12} = \frac{.75 \times 24^3}{12} = 864 \text{ IN}^4 \times 2 \text{ WEBS} = 1728 \text{ IN}^4$$

NET MOMENT OF INERTIA:

$$2228 + 882 = \boxed{3110 \text{ IN}^4}$$

GROSS MOMENT OF INERTIA

$$2228 + 1728 = \boxed{3956 \text{ IN}^4}$$

SECTION MODULUS:

$$S = \frac{I}{c} = \frac{3110}{12} = \boxed{259 \text{ IN}^3}$$

BEAM WEIGHT:

CROSS-SECTION: $4[(1.5)(3.5)] + 2[(.75)(24)] = 57 \text{ IN}^2$

× 12 IN. [illegible]

684 IN^3

$$684 \text{ IN}^3 = .4 \text{ FT}^3 \times 40 \text{ \#/FT}^3 = 16 \text{ PLF} \times 16' = \boxed{256 \text{ \#}}$$

PAGE 2 OF 2

BENDING DESIGN

RESISTIVE MOMENT

$M = fS = 1550 \text{ PSI} \times 259 \text{ IN}^3 = 401{,}450''\#$

BENDING MOMENT

$$M = \frac{W\ell}{8} = \frac{(7680 + 256)(192)}{8} = 190{,}464''\#$$

$\underline{190{,}464 < 401{,}450 \therefore \text{BNDG. OK}}$

HORIZONTAL SHEAR

$$Q = 2\left[(1.5)(3.5)\left(12 - \frac{3.5}{2}\right)\right] + 2\left[(.75)(12)(6)\right] = 216 \text{ IN}^3$$

$$f_v = \frac{VQ}{I_n \Sigma t_w} = \frac{3967 \times 216}{3110 \times 1.5} = \underline{184 \text{ PSI} < F_v \text{ OF } 250 \text{ PSI} \therefore f_v \text{ OK}}$$

ROLLING SHEAR

$$Q_{fl} = 2\left[(1.5)(3.5)\left(12 - \frac{3.5}{2}\right)\right] = 108 \text{ IN}^3$$

$$f_s = \frac{VQ_{fl}}{2dI_n} = \frac{3967 \times 108}{2 \times 3.5 \times 3110} = \underline{19.7 \text{ PSI} < F_s \text{ OF } 37.5 \text{ PSI} \therefore f_s \text{ OK}}$$

DEFLECTION

TOTAL LOAD:

$$\Delta_{\text{ALLOWABLE}} = \frac{\ell}{240} = \frac{192''}{240} = .8''$$

Δ ACTUAL

DUE TO BNDG. $\Delta = \dfrac{5W\ell^3}{384EI_n} = \dfrac{5 \times 7934 \times 192^3}{384 \times 1{,}800{,}000 \times 3011} = .13''$

DUE TO SHEAR & BNDG: (APPROX.)

1.5 (FROM TABLE) $\times .13'' = .195'' < .8''$

DEFLECTION → INSIGNIF.

LATERAL SUPPORT

POSITIVE CONNECTION BY TRUSSES @ 2'-0" → ADEQUATE

TRIAL SECTION IS ENTIRELY ADEQUATE

Chapter Six

FINALLY

Summary

Built-up plywood box beams, one of a number of engineered plywood components, have been around for nearly forty years. They have been used in a number of various applications from conveyor belts to bridges. Their main use, however, continues to be in light frame construction; particularly in manufactured housing, e.g. Wausau Homes. They offer several distinct advantages, over solid wood beams, notably good weight-to-strength ratio, superior performance in shear, and relatively low in-place cost.

The design of box beams was initially developed by the Forest Products Laboratory in Madison Wisconsin. In the past several years, however, refinements in the design procedure have been promulgated by the American Plywood Association.

The design procedure requires the designer to assume a section and then ascertain its structural integrity with respect to the loading conditions. Typically the designer needs to investigate the trial section for bending, horizontal and rolling shear, deflection, web stiffening, and lateral stability.

Conclusions

In the introduction to this piece of research, a statement was made to the effect that the study of built-up plywood box beams would make a valuable addition to a course in structural wood design. The researcher is now convinced that that was a valid statement.

The study has indicated that the design of box beams requires a background in engineering, at least at the technician level. It is the opinion of the researcher that the design of plywood beams lies within the grasp of the properly motivated technician-in-training. Chapter five of the study presents instructional materials and suggestions for adding box beam design to a structural wood design course at the technical school/community college level.

Recommendations

The design procedure presented in chapter four was based on literature that is at least five years old. A 1978 edition of Robert Hoyle's Wood Technology in the Design of Structures, Missoula, Montana: Mountain Press, should be available quite soon. The researcher recommends that the design procedure in chapter four be compared with Mr. Hoyle's new book and the latest information from the American Plywood Association; there may have been some changes made in the design procedure, based on recent research.

As a result of investigating the literature, the researcher feels that an additional comment is appropriate at this time. The built-up plywood box beam is but one of several engineered plywood components. The logical direction for this or another researcher to take with respect to technical instruction in structural design is to investigate and develop instructional units for these other plywood components. Presently the list might consist of stressed-skin panels, folded plates, shear walls and diaphragms. Because of the research and development efforts of such organizations as the American Plywood Association, the Forest Products Laboratory and other, there is likely to be new applications of structural plywood in the future.

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APPENDIX A

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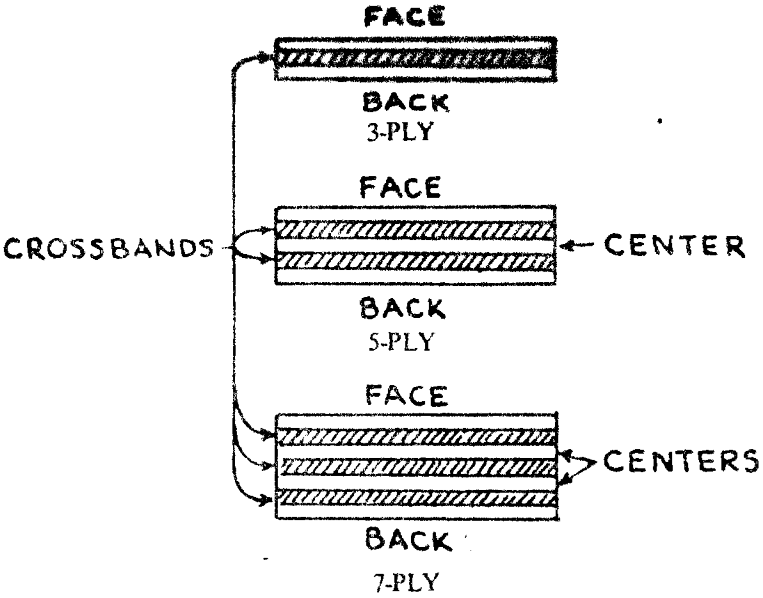
APPENDIX B

Plywood Sizes, Nomenclature & Grading Criteria



Plywood Nomenclature

Plies Thickness	3	4	5	7
5/16	X			
3/8	X			
1/2	X	X	X	
5/8	X	X	X	
3/4			X	
13/16			X	
7/8			X	X
1				X
1 1/8				X

Typical Plywood Thickness & Number of Plys

APPENDIX C

Allowable Stresses for Visually Graded Lumber

This appendix contains allowable stresses for a selected few lumber species. Students in a structural wood design course would have access to a more complete table of allowable stresses.

The following tables are taken from a supplement to the 1971 edition of National Design Specification for Stress-Grade Lumber and Its Fastenings and also the November 1972 Addendum to the same publication.

Note: Data in the tables was determined in accordance with American Society for Testing and Materials Designations D245-71 "Methods for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber" and D2555-70 "Methods for Establishing Clear Wood Strength Values."

APPENDIX D

Allowable Stresses, etc. for Plywood

APPENDIX E

Typical Beam Formulas

APPENDIX F

Suggested Box Beam Specification

VITA

Michael J. Sneddon

Waterloo, Iowa 50701

Born:

Educational Background:

Galesburg High School (1965)
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Associate Degree (1967)
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Bachelor of Science Degree (1973)
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(Hopefully Spring 1978) Master of Arts in Technology Degree
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Employment History:

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Draftsman for P&M Lustrolite Company
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1967 - 1970
United States Army

1971 -1973
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Carbondale, Illinois

1973 to present
Architectural Drafting Instructor
Hawkeye Institute of Technology
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