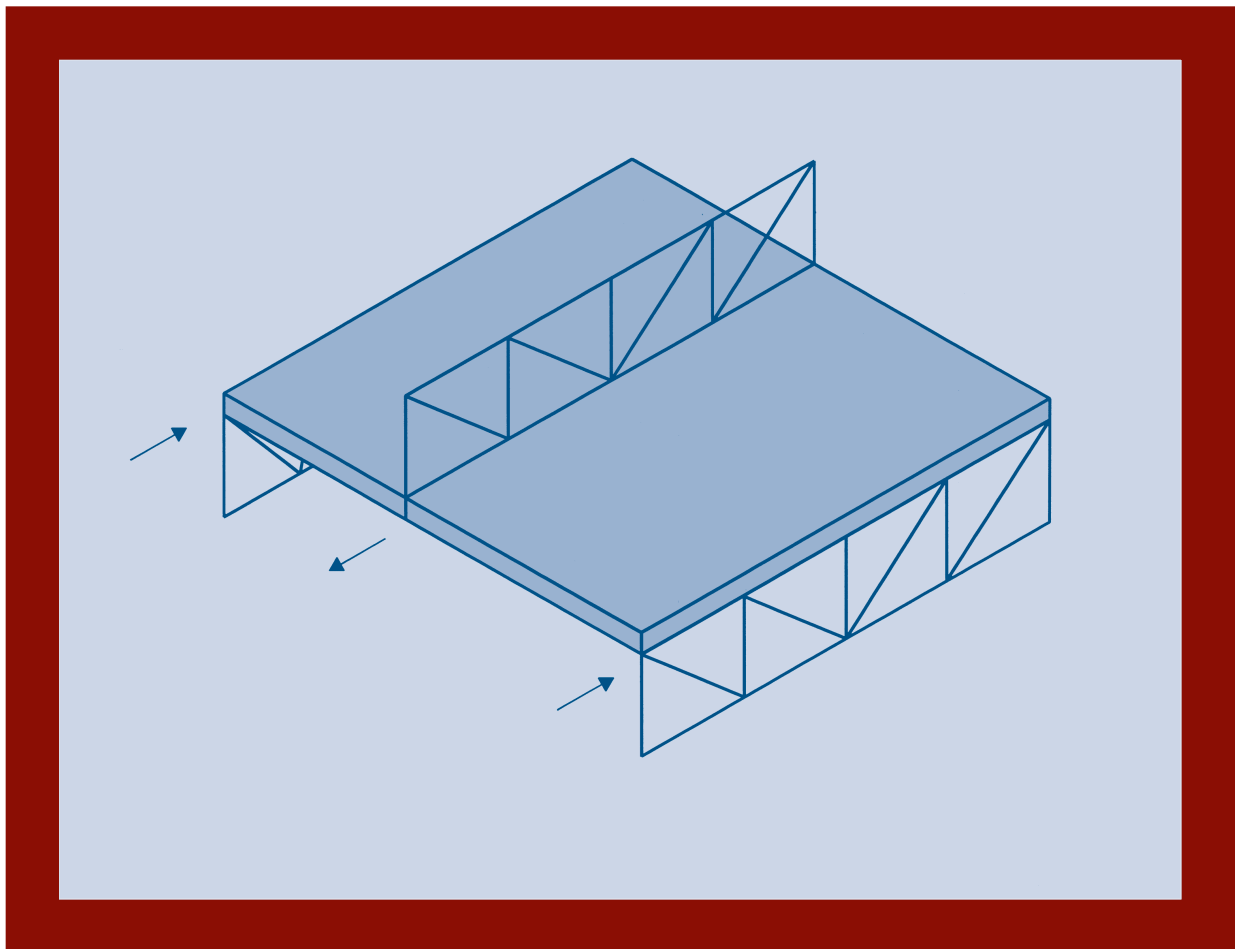




14

Steel Design Guide Series

Staggered Truss Framing Systems



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Steel Design Guide

Staggered Truss Framing Systems

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PREFACE

In recent years staggered truss steel framing has seen a nationwide renaissance. The system, which was developed at MIT in the 1960s under the sponsorship of the U.S. Steel Corporation, has many advantages over conventional framing, and when designed in combination with precast concrete plank or similar floors, it results in a floor-to-floor height approximately equal to flat plate construction.

Between 1997 and 2000, the authors had the privilege to design six separate staggered truss building projects. While researching the topic, the authors realized that there was little or no written material available on the subject. Simultaneously, the AISC Task Force on Shallow Floor Systems recognized the benefits of staggered trusses over other systems and generously sponsored the development of this design guide. This design guide, thus, summarizes the research work and the practical experience gathered.

Generally, in staggered-truss buildings, trusses are normally one-story deep and located in the demising walls between rooms, with a Vierendeel panel at the corridors. The trusses are prefabricated in the shop and then bolted in the field to the columns. Spandrel girders are bolted to the columns and field welded to the concrete plank. The exterior walls are supported on the spandrel girders as in conventional framing.

Staggered trusses provide excellent lateral bracing. For mid-rise buildings, there is little material increase in staggered trusses for resisting lateral loads because the trusses are very efficient as part of lateral load resisting systems. Thus, staggered trusses represent an exciting and new steel application for residential facilities.

This design guide is written for structural engineers who have building design experience. It is recommended that the readers become familiar with the material content of the references listed in this design guide prior to attempting a first structural design. The design guide is written to help the designer calculate the initial member loads and to perform approximate hand calculations, which is a requisite for the selection of first member sizes and the final computer analyses and verification.

Chapter 7 on Fire Resistance was written by Esther Slubski and Jonathan Stark from the firm of Perkins Eastman Architects. Section 5.1 on Seismic Strength and Ductility Requirements was written by Robert McNamara from the firm of McNamara Salvia, Inc. Consulting Structural Engineers.

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Table of Contents

Authors.....	v
Preface.....	v
Acknowledgements.....	vi

Chapter 1 Staggered Truss Framing Systems..... 1

1.1 Advantages of Staggered Trusses.....	1
1.2 Material Description.....	1
1.3 Framing Layout.....	2
1.4 Responsibilities.....	3
1.5 Design Methodology.....	4
1.6 Design Presentation.....	4

Chapter 2 Diaphragm Action with Hollow Core Slabs..... 7

2.1 General Information.....	7
2.2 Distribution of Lateral Forces.....	7
2.3 Transverse Shear in Diaphragm.....	9
2.4 Diaphragm Chords.....	10

Chapter 3 Design of Truss Members..... 15

3.1 Hand and Computer Calculations.....	15
3.2 Live Load Reduction.....	15
3.3 Gravity Loads.....	15
3.4 Lateral Loads.....	17
3.5 Load Coefficients.....	17
3.6 Vertical and Diagonal Members.....	19
3.7 Truss Chords.....	19
3.8 Computer Modeling.....	19
3.9 Columns.....	21

Chapter 4 Connections in Staggered Trusses..... 25

4.1 General Information.....	25
4.2 Connection Between Web Member and Gusset Plate.....	25
4.3 Connection Between Gusset Plate and Chord.....	27
4.4 Design Example.....	27
4.5 Miscellaneous Considerations.....	27

Chapter 5 Seismic Design..... 29

5.1 Strength and Ductility Design Requirements.....	29
5.2 New Seismic Design Considerations for Precast Concrete Diaphragms.....	29
5.3 Ductility of Truss Members.....	29
5.4 Seismic Design of Gusset Plates.....	30
5.5 New Developments in Gusset Plate to HSS Connections.....	31

Chapter 6 Special Topics..... 33

6.1 Openings.....	33
6.2 Mechanical Design Considerations.....	33
6.3 Plank Leveling.....	33
6.4 Erection Considerations.....	33
6.5 Coordination of Subcontractors.....	34
6.6 Foundation Overturning and Sliding.....	34
6.7 Special Conditions of Symmetry.....	35
6.8 Balconies.....	35
6.9 Spandrel Beams.....	35

Chapter 7 Fire Protection of Staggered Trusses..... 37

References..... 39

Chapter 1

INTRODUCTION

1.1 Advantages of Staggered Truss Framing Systems

The staggered-truss framing system, originally developed at MIT in the 1960s, has been used as the major structural system for certain buildings for some time. This system is efficient for mid-rise apartments, hotels, motels, dormitories, hospitals, and other structures for which a low floor-to-floor height is desirable. The arrangement of story-high trusses in a vertically staggered pattern at alternate column lines can be used to provide large column-free areas for room layouts as illustrated in Fig. 1.1. The staggered-truss framing system is one of the only framing system that can be used to allow column-free areas on the order of 60 ft by 70 ft. Furthermore, this system is normally economical, simple to fabricate and erect, and as a result, often cheaper than other framing systems.

One added benefit of the staggered-truss framing system is that it is highly efficient for resistance to the lateral loading caused by wind and earthquake. The stiffness of the system provides the desired drift control for wind and earthquake loadings. Moreover, the system can provide a significant amount of energy absorption capacity and ductile deformation capability for high-seismic applications. When conditions are proper, it can yield great economy and maximum architectural and planning flexibility.

It also commonly offers the most cost-efficient possibilities, given the project's scheduling considerations. The staggered-truss framing system is one of the quickest available methods to use during winter construction. Erection and enclosure of the buildings are not affected by prolonged sub-freezing weather. Steel framing, including spandrel beams and precast floors, are projected to be erected at the

rate of one floor every five days. Once two floors are erected, window installation can start and stay right behind the steel and floor erection. No time is lost in waiting for other trades such as bricklayers to start work. Except for foundations and grouting, all "wet" trades are normally eliminated.

Savings also occur at the foundations. The vertical loads concentrated at a few columns normally exceed the uplift forces generated by the lateral loads and, as a result, uplift anchors are often not required. The reduced number of columns also results in less foundation formwork, less concrete, and reduced construction time. When used, precast plank is lighter than cast-in-place concrete, the building is lighter, the seismic forces are smaller, and the foundations are reduced.

The fire resistance of the system is also good for two reasons. First, the steel is localized to the trusses, which only occur at every 58 to 70 ft on a floor, so the fireproofing operation can be completed efficiently. Furthermore, the trusses are typically placed within demising walls and it is possible that the necessary fire rating can be achieved through proper construction of the wall. Also, the elements of the trusses are by design compact sections and thus will require a minimum of spray-on fireproofing thickness.

1.2 Material Description

A staggered-truss frame is designed with steel framing members and concrete floors. Most often, the floor system is precast concrete hollow-core plank. Other options, including concrete supported on metal deck with steel beams or joists, can be used.

With precast plank floors, economy is achieved by "stretching" the plank to the greatest possible span. 8-in.-thick plank generally can be used to span up to 30 ft, while 10-in.-thick plank generally can be used to span up to 36 ft. Specific span capabilities should be verified with the specific plank manufacturer. Therefore, the spacing of the trusses has a close relationship to the thickness of plank and its ability to span. 6-in.-thick precast plank is normally only used with concrete topping.

Hollow core plank is manufactured by the process of extrusion or slip forming. In both cases the plank is prestressed and cambered. The number of tendons and their diameter is selected for strength requirements by the plank manufacturer's engineer based upon the design instructions provided by the engineer of record.

The trusses are manufactured from various steels. Early buildings were designed with chords made of wide-flange sections and diagonal and vertical members made of chan-

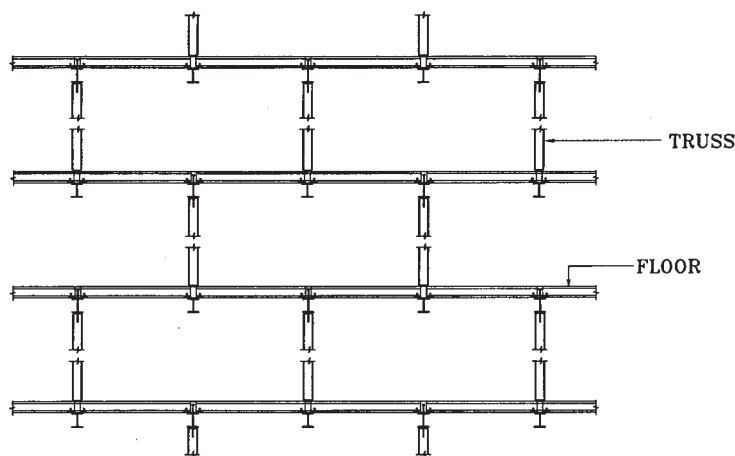


Fig. 1.1 Staggered-truss system-vertical stacking arrangement.

Table 1.1 Material Guide			
	Section	ASTM	Fy (ksi)
Columns and Truss Chords	Wide Flange	A992 or A572	50
Web Members (Vertical and Diagonal)	Hollow Structural Section	A500 grade B or C	46 or 50 (rectangular)
Gusset Plates	Plates	A36 or A572	36 or 50

nels. The channels were placed toe-to-toe, welded with separator plates to form a tubular shape. Later projects used hollow structural sections (HSS) for vertical and diagonal members.

Today, the most common trusses are designed with W10 chords and HSS web members (verticals and diagonals) connected with gusset plates. The chords have a minimum width of 6 in., required to ensure adequate plank bearing during construction. The smallest chords are generally W10x33 and the smallest web members are generally HSS4x4x1/4. The gusset plates are usually 1/2-in. thick.

The trusses are manufactured with camber to compensate for dead load. They are transported to the site, stored, and then erected, generally in one piece. Table 1.1 is a material guide for steel member selection. Other materials, such as A913, may be available (see AISC Manual, Part 2).

The plank is connected to the chords with weld plates to ensure temporary stability during erection. Then, shear stud connections are welded to the chords, reinforcing bars are placed in the joints, and grout is placed. When the grout cures, a permanent connection is achieved through the

welded studs as illustrated in Fig. 1.2. Alternatively, guying or braces may also be used for temporary stability during construction.

The precast plank is commonly manufactured with 4,000 psi concrete. The grout commonly has 1,800 psi compressive strength and normally is a 3:1 mixture of sand and Portland cement. The amount of water used is a function of the method used to place the grout, but will generally result in a wet mix so joints can be easily filled. Rarely is grout strength required in excess of 2,000 psi. The grout material is normally supplied and placed by the precast erector.

1.3 Framing Layout

Fig. 1.3 shows the photo of a 12-story staggered-truss apartment building located in the Northeast United States. Its typical floor plan is shown in Fig. 1.4. This apartment building will be used as an example to explain the design and construction of staggered-truss-framed structures throughout this design guide. The floor system of this 12-story proj-

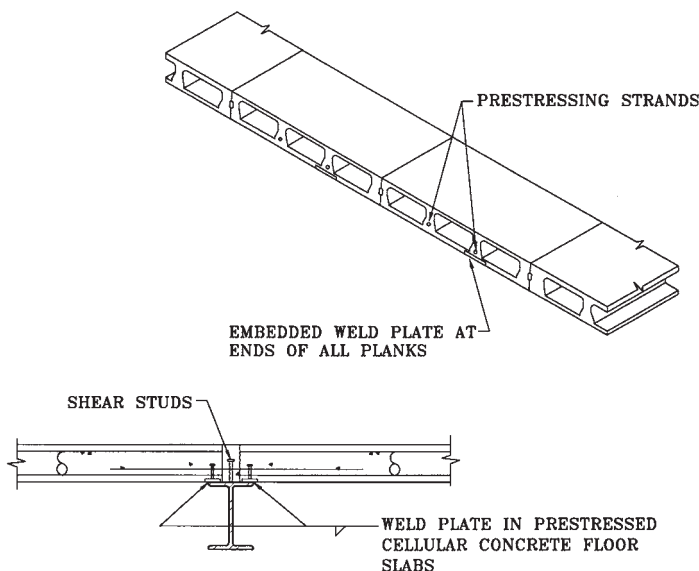


Fig. 1.2 Concrete plank floor system.



Fig. 1.3 Staggered truss apartment building.

ect utilizes 10-in.-thick precast concrete plank. The stairs and elevator openings are framed with steel beams. The columns are oriented with the strong axis parallel to the short building direction. There are no interior columns on truss bents; only spandrel columns exist. There are interior columns on conventionally framed bents.

Moment frames are used along the long direction of the building, while staggered trusses and moment frames are used in the short direction.

Two different truss types are shown on the plan, namely trusses T1 and T2. Fig. 1.5 shows truss T1B and Fig. 1.6 shows truss T2C. Truss T1B is Truss Type 1 located on grid line B, and T2C is Truss Type 2 located on grid line C. The truss layout is always Truss Type 1 next to Type 2 to minimize the potential for staggered truss layout errors. Each truss is shown in elevation in order to identify member sizes and special conditions, such as Vierendeel panels. Any special forces or reactions can be shown on the elevations where they occur. The structural steel fabricator/detailer is provided with an explicit drawing for piece-mark identification. Camber requirements should also be shown on the elevations.

Table 1.2 shows the lateral forces calculated for the building. For this building, which is located in a low-seismic zone, wind loads on the wide direction are larger than seismic forces, and seismic forces are larger in the narrow direction. So that no special detailing for seismic forces would be required, a seismic response modification factor R of 3 was used in the seismic force calculations. The distributed gravity loads of the building are listed below, where plate loads are used for camber calculations.

Dead Loads

10" precast hollow core plank	75 psf
Leveling compound	5
Structural steel	5
Partitions	12
Dead Loads	97 psf

Plate Loads

10" precast hollow core plank	75 psf
Structural steel	5
Plate Loads	80 psf

Live Loads 40 psf

Wall Loads

Brick	40 psf
Studs	3
Sheet rock	3
Insulation	2
Wall Loads	48 psf

The loads listed above are used in the calculations that follow.

1.4 Responsibilities

The responsibilities of the various parties to the contract are normally as given on the *AISC Code of Standard Practice for Steel Buildings and Bridges*. All special conditions should be explicitly shown on the structural drawings.

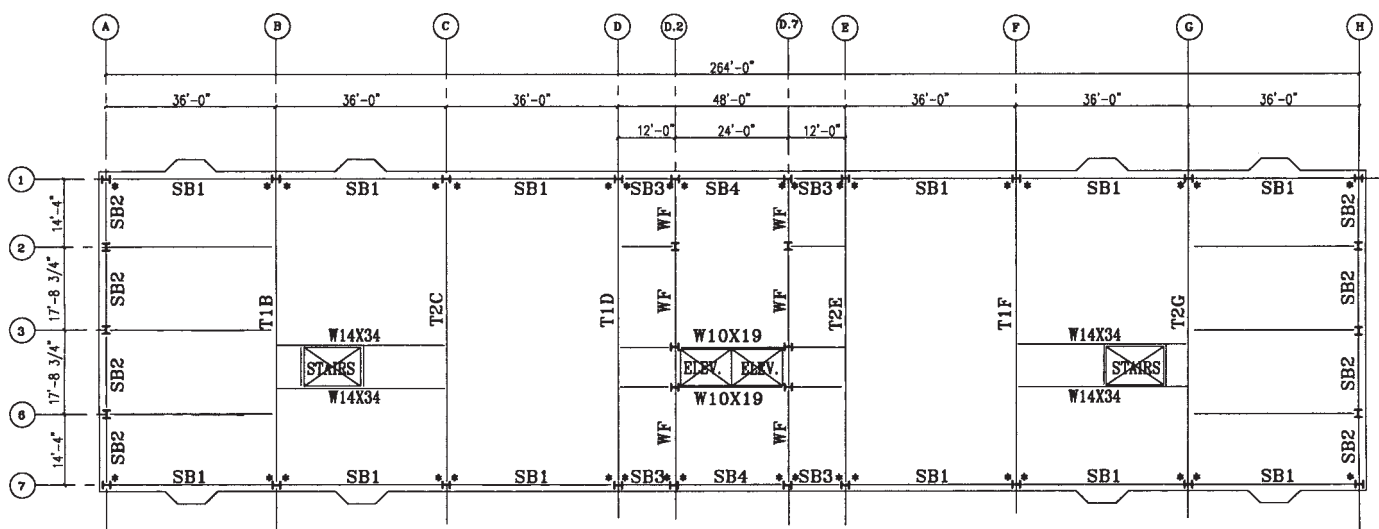


Fig. 1.4 Typical floor framing plan. Note: * indicates moment connections.

Table 1.2 Wind and Seismic Forces (All Loads are Service Loads)						
	WIND (ON WIDE DIRECTION)			SEISMIC (BOTH DIRECTIONS)		
	Lateral Load	Story Shear	Φ_h	Lateral Load Service	Story Shear	Φ_h
Floor	V_j (kips)	V_w (kips)	(%)	V_j (kips)	V_w (kips)	(%)
Roof	107	107	9%	83	83	13%
12	105	212	18%	90	173	26%
11	103	315	27%	82	255	39%
10	103	418	36%	78	333	51%
9	103	521	45%	65	398	61%
8	98	619	54%	58	456	70%
7	96	715	62%	52	508	78%
6	93	808	70%	44	552	85%
5	91	899	78%	39	591	91%
4	86	985	86%	29	620	95%
3	84	1069	93%	21	641	98%
2	79	1148	100%	11	652	100%
Ground						

1.5 Design Methodology

The design of a staggered-truss frame is done in stages. After a general framing layout is completed, gravity, wind, and seismic loads are established. Manual calculations and member sizing normally precede the final computer analysis and review. For manual calculations, gravity and lateral loads are needed and the member sizes are then obtained through vertical tabulation.

The design methodology presented in this design guide is intended to save time by solving a typical truss only once for gravity loads and lateral loads, then using coefficients to obtain forces for all other trusses. The method of coefficients is suitable for staggered trusses because of the repetition of the truss geometry and because of the “racking” or shearing behavior of trusses under lateral loads. This is similar to normalizing the results to the “design truss”.

Approximate analysis of structures is needed even in today’s high-tech computer world. At least three significant reasons are noted for the need for preliminary analysis as following:

1. It provides the basis for selecting preliminary member sizes, which are needed for final computer input and verification.
2. It provides a first method for computing different designs and selecting the preferred one.
3. It provides an independent method for checking the reports from a computer output.

Theoretically, staggered-truss frames are treated as structurally determinate, pin-jointed frames. As such, it is assumed that no moment is transmitted between members across the joints. However, the chords of staggered trusses

are continuous members that do transmit moment, and some moment is always transmitted through the connections of the web members.

The typical staggered-truss geometry is that of a “Pratt truss” with diagonal members intentionally arranged to be in tension when gravity loads are applied. Other geometries, however, may be possible.

1.6 Design Presentation

The structural drawings normally include floor framing plans, structural sections, and details. Also, structural notes and specifications are part of the contract documents. Floor plans include truss and column layout, stairs and elevators, dimensions, beams, girders and columns, floor openings, section and detail marks. A column schedule indicates column loads, column sizes, location of column splices, and sizes of column base plates.

The diaphragm plan and its chord forces and shear connectors with the corresponding forces must be shown. It is also important that the plan clearly indicate what items are the responsibilities of the steel fabricator or the plank manufacturer. Coordination between the two contractors is critical, particularly for such details as weld plate location over stiffeners, plank camber, plank bearing supports, and clearances for stud welding. Coordination meetings can be particularly helpful at the shop drawing phase to properly locate plank embedded items.

In seismic areas, the drawings must also indicate the Building Category, Seismic Zone, Soil Seismic Factor, Importance Factor, required value of R , and Lateral Load Resisting System.



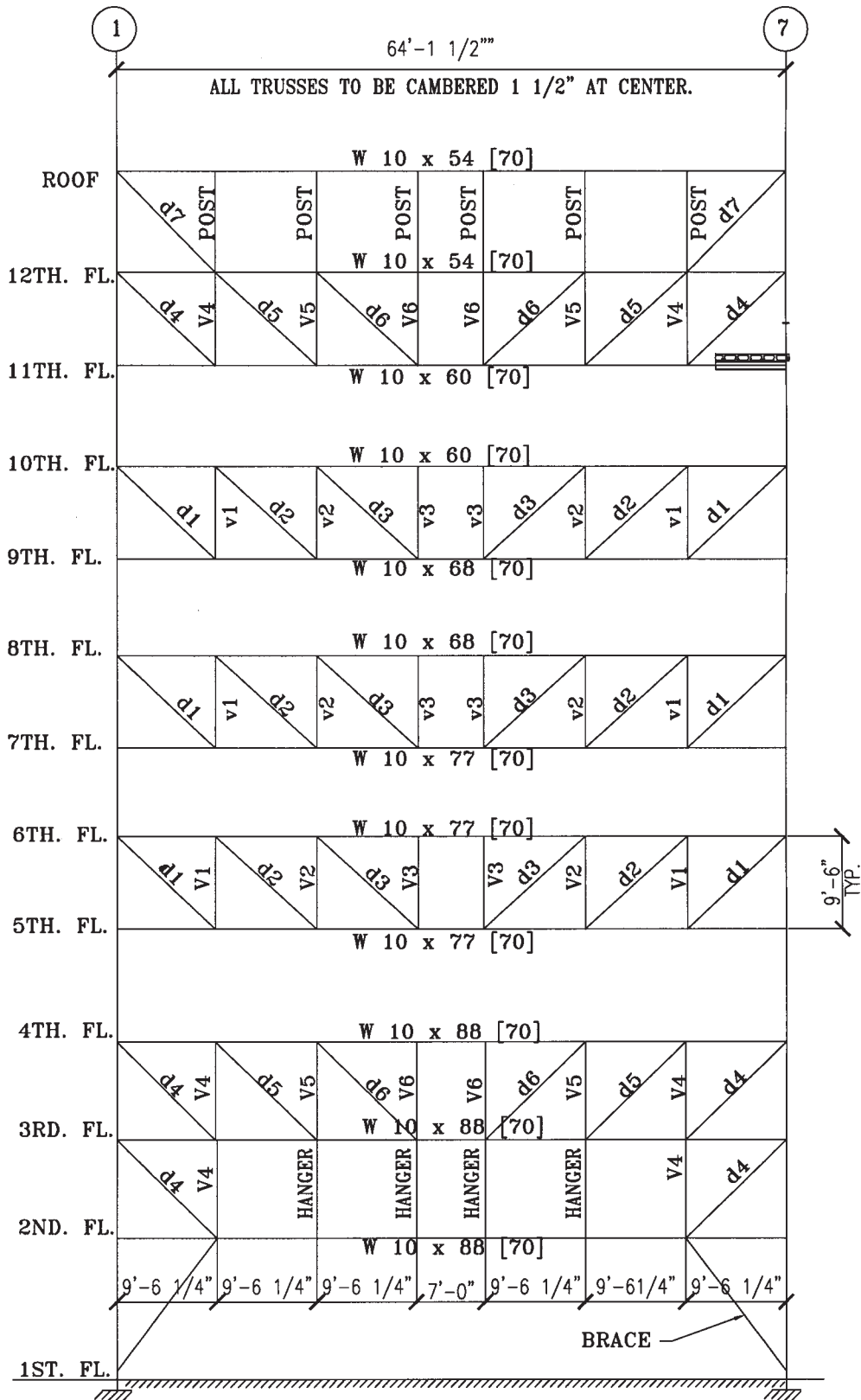


Fig. 1.6 Staggered truss type T2C. Note: [] indicates number of composite studs (3/4" dia., 6" long, equally spaced).

Chapter 2

DIAPHRAGM ACTION WITH HOLLOW-CORE SLABS

2.1 General Information

It is advisable to start the hand calculations for a staggered-truss building with the design of the diaphragms. In a staggered-truss building, the diaphragms function significantly different from diaphragms in other buildings because they receive the lateral loads from the staggered trusses and transmit them from truss to truss. The design issues in a hollow-core diaphragm are stiffness, strength, and ductility, as well as the design of the connections required to unload the lateral forces from the diaphragm to the lateral-resisting elements. The *PCI Manual for the Design of Hollow Core Slabs* (PCI, 1998) provides basic design criteria for plank floors and diaphragms.

Some elements of the diaphragm design may be delegated to the hollow core slab supplier. However, only the engineer of record is in the position to know all the parameters involved in generating the lateral loads. If any design responsibility is delegated to the plank supplier, the location and magnitude of the lateral loads applied to the diaphragm and the location and magnitude of forces to be transmitted to lateral-resisting elements must be specified.

An additional consideration in detailing diaphragms is the need for structural integrity. ACI 318 Section 16.5 provides the minimum requirements to satisfy structural integrity. The fundamental requirement is to provide a complete load path from any point in a structure to the foundation. In staggered-truss buildings all the lateral loads are transferred from truss to truss at each floor. The integrity of each floor diaphragm is therefore significant in the lateral load resistance of the staggered-truss building.

2.2 Distribution of Lateral Forces

The distribution of lateral forces to the trusses is a structurally indeterminate problem, which means that deformation compatibility must be considered. Concrete diaphragms are generally considered to be rigid. Analysis of flexible diaphragms is more complex than that of rigid diaphragms. However, for most common buildings subject to wind forces and low-seismic risk areas, the assumption of rigid diaphragms is reasonable. If flexible diaphragms are to be analyzed, the use of computer programs with plate-element options is recommended.

For the example shown in this design guide, a rigid diaphragm is assumed for the purpose of hand calculations and for simplicity. This assumption remains acceptable as long as the diaphragm lateral deformations are appropriately limited. One way to ensure this is to limit the

diaphragm aspect ratio and by detailing it such that it remains elastic under applied loads. From Smith and Coull (1991), the lateral loads are distributed by the diaphragm to trusses as follows:

$$V_i = V_s + V_{\text{TORS}} \quad (2-1)$$

where

$$\begin{aligned} V_i &= \text{truss shear due to lateral loads} \\ V_s &= \text{the translation component of shear} \\ &= V_w \times GA_i / \Sigma GA_i \end{aligned} \quad (2-2)$$

$$\begin{aligned} V_{\text{TORS}} &= \text{the torsion component of shear} \\ &= V_w \times e \times \bar{x}_i GA_i / GJ \end{aligned} \quad (2-3)$$

where

$$\begin{aligned} GA_i &= \text{Shear rigidity of truss} \\ \Sigma GA_i &= \text{Building translation shear rigidity} \\ GJ &= \text{Building torsion shear rigidity} \\ e &= \text{Load eccentricity} \\ \bar{x}_i &= \text{Truss coordinate (referenced to the center of rigidity (CR))} \\ V_w &= \text{Story shear due to lateral loads (see Table 1.2)} \end{aligned}$$

Smith and Coull (1991) provide expressions for story shear deformations for a single brace as (Fig. 2.1):

$$\Delta = \frac{V}{E} \left(\frac{d^3}{L^2 A_d} + \frac{L}{A_g} \right) \quad (2-4)$$

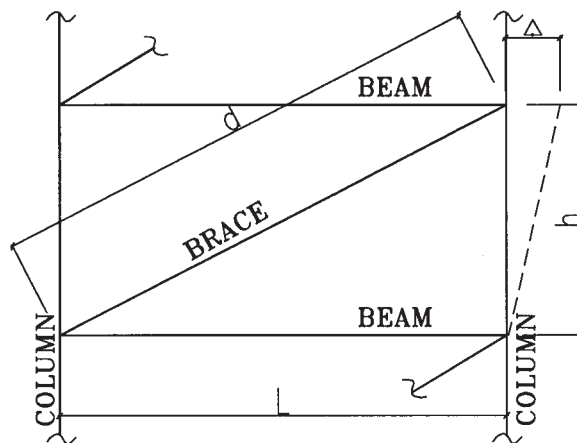


Fig. 2.1 Story shear deformation for single brace.

where

V = shear force applied to the brace
 E = modulus of elasticity
 d = length of the diagonal
 L = length between vertical members
 A_d = sectional area of the diagonal
 A_g = sectional area of the upper girder

The shear rigidity GA is then computed as:

$$GA = \frac{Vh}{\Delta} = \frac{Eh}{d^3 / (L^2 A_d) + L / A_g} \quad (2-5)$$

where h is the story height. The overall truss shear rigidity is the sum of the shear rigidities of all the brace panels in that truss. The reader may use similar expressions to determine approximate values for GA in buildings where variations in stiffness occur.

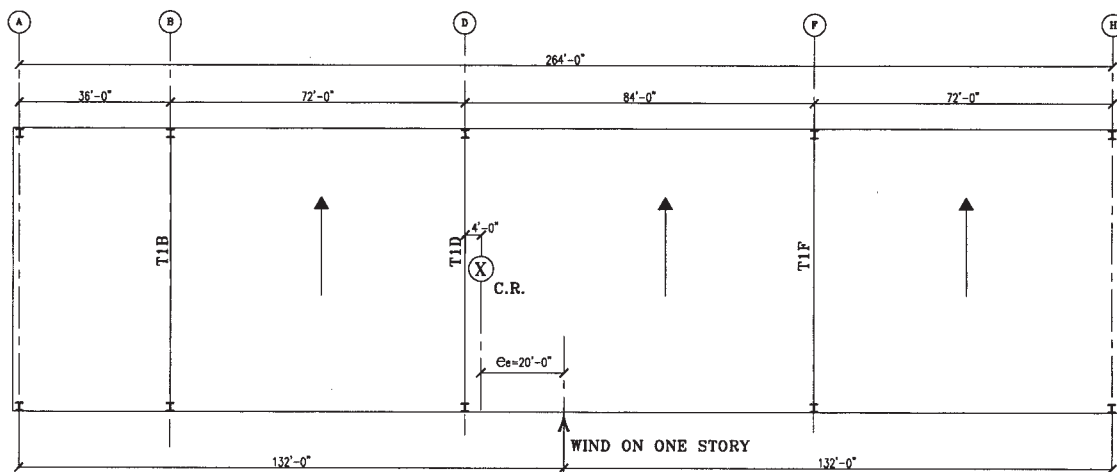
The hand calculations are started by finding the center of rigidity, which is defined as the point in the diaphragm about which the diaphragm rotates when subject to lateral loads. The formula for finding the center of rigidity is (Smith and Coull, 1991; Taranath, 1997):

$$x = \sum x_i GA_i / \sum GA_i \quad (2-6)$$

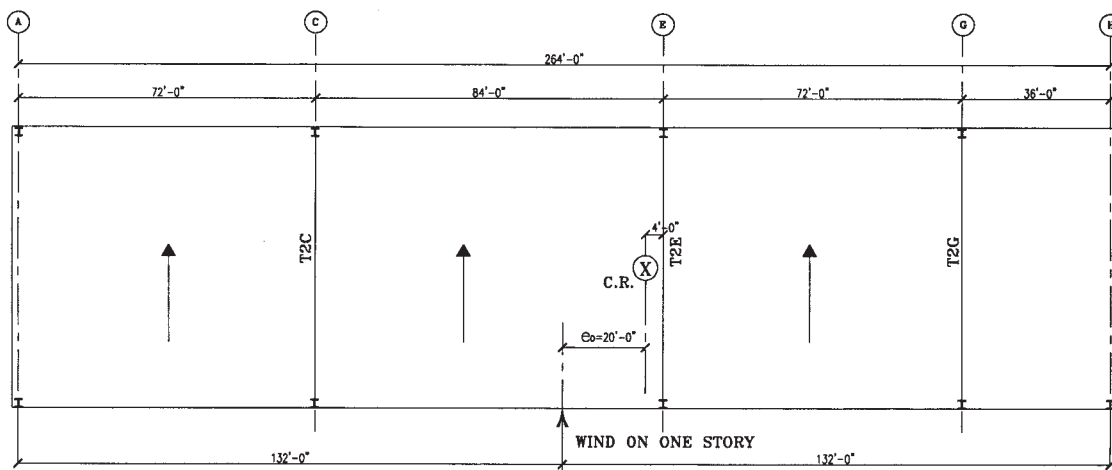
For staggered-truss buildings, the center of rigidity is calculated separately at even floors and odd floors. Assuming that the trusses of the staggered-truss building shown in Figs. 1.5 and 1.6 have approximately equal shear rigidity, GA_i , per truss, the center of rigidity of each floor is calculated as follows (see Fig. 2.2):

Even Floors

Truss	x_i (ft)
T1B	36
T1D	108
T1F	192
Σ	$\Sigma x_i = 336$
	$x_e = 336/3 = 112'$



(a)—Even Floor



(b)—Odd Floor

Fig. 2.2 Center of rigidity for lateral loads.