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Blast Design of Steel Structures to Prevent Progressive Collapse

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Abstract

Structural design of buildings to withstand blast explosions has typically been limited to petrochemical facilities and military structures. With increased terrorist activity throughout the world, government and commercial buildings have now become bomb threat targets. Various preventative measures are available to limit building damage caused by bombing. A primary objective is to incorporate measures to prevent a catastrophic structural collapse. This paper illustrates planning and presents details for structural steel buildings to mitigate progressive collapse of floors due to the loss of columns in a bomb explosion. When combined with other security design guidelines, saving lives and preventing injuries can be achieved in cost-effective ways.

Introduction

The structural engineering profession has experienced many significant and complex changes in the past several decades. Higher strength materials and improved computational methods allow us to design buildings to new limits of height and span. Recent events involving earthquakes, hurricanes, tornadoes, etc. produced many unexpected structural problems. This has often resulted in specific building code changes aimed at avoiding similar problems in the future. A new consideration confronting the structural engineer is the increased threat of terrorist bomb blasts. Until recently, terrorist attacks were thought to be a foreign problem. However, planned intentional explosions have now caused severe damage or collapse to several buildings in this country. Due to growing public awareness and concern, structural engineers are increasingly requested to design buildings to withstand the effects of terrorist blasts. New federal government facilities must now be designed to resist explosive attack threats. Other public- and private-sector owners are giving attention to security and blast design for their buildings. Several levels of blast protection are possible, but priority is usually given to the critical elements needed to prevent progressive collapse of the floors.

Structural engineers are familiar with conventional building loads due to gravity, wind, seismic, etc., but are generally inexperienced in developing structural systems to prevent progressive collapse caused by the loss of columns in an explosion. The majority of technical literature on blast resistant design is directed towards large industrial or military installations. Blast consultants have tended to recommend ductile reinforced concrete rather than structural steel because of its high resistance and mass properties. For commercial or institutional building projects, the practicing engineer may feel that structural options and reference sources are limited.

This paper will provide a basic description of bomb blasts and discuss the critical goal of preventing progressive collapse in a structure. Blast recommendations appropriate for conventional structural steel buildings will also be presented. An example of a recently designed government building detailed for progressive collapse will be described in order to demonstrate the feasibility and economy of structural steel for this special application.

Characteristics of Bomb Blasts

Several types of explosives are available for a bombing attack. This can range from easily purchased ingredients for ANFO bombs (a mixture of ammonium nitrate and fuel oil) used in the Oklahoma City explosion, to manufactured materials such as TNT, C-4, and Sentex. Methods to determine bomb blast loading will normally present the charge weight in terms of equivalent weight of TNT.

The significant feature of a blast explosion is the sudden release of energy into the atmosphere which results in a pressure wave transient, more commonly known as a blast wave (see Figure 1). With the detonation of a TNT-like bomb, peak blast pressures develop almost instantaneously, then decrease as the expanding shock/pressure wave travels outward from the explosion. Blast waves are reflected when they strike an object or surface, resulting in amplification of the initial peak pressure. The resulting pressure can be several times greater than the initial pressure. The magnitude of amplification depends upon the intensity of the blast, the angle of incidence of the blast wave to the reflecting surface, and the type of blast wave under consideration. The interaction between a bomb blast and a building is very complex and involves variables that are not reliably predictable. The Army technical manual TM 5-1300 (Department 1990) provides explosive information and blast analysis methodologies for many conditions.

It is important to note that the most effective way of protecting a building from a bomb blast is not by designing the structure for larger forces. Structural hardening is costly and the engineer cannot reasonably design the entire building for close-in blast. Instead, detection and increased standoff distance must be the primary means of defense (Ettouney 1996). Additional strengthening should be considered as a last resort.

Avoiding Progressive Collapse

The primary objective of blast design is to save lives, prevent injuries, and avoid progressive collapse so that victims can be evacuated. There are three basic approaches to blast design:

1. Blast loads can be reduced by increasing standoff distance from the bomb.
2. The structure can be strengthened to resist higher loads.
3. Higher levels of risk can be accepted.

A combination of all three items, in various degrees, is generally acknowledged as the best solution to a terrorist bomb threat.

Whether a building is constructed with steel or concrete, economical blast resistance requires a structural system having a well-distributed, redundant lateral load resisting system and ductile connections capable of undergoing large inelastic rotations without failing. This is achieved by applying principles and detailing practices developed for seismic design. The essential requirement is to prevent progressive collapse of the floors. As a minimum, the structure should be designed for the loss of one primary column at the building perimeter for the first two floors above grade. The resulting postdamage mechanism is a sagging beam spanning two bays as depicted in Figure 2. The sagging beam must be capable of sustaining large deflections by catenary action in order to support any floors above. At the failed column locations, effective continuity elements are necessary to form a plastic hinge and to transfer axial load developed by the catenary. Specific details applicable to steel buildings are discussed in the following section.

Structural Steel Blast Resistance

A common perception is that reinforced concrete is best material for buildings subject to bomb explosions. While concrete has inherently large mass with desirable blast resistance qualities, it is not always the most appropriate material choice. For example, column and beam dimensions will usually be larger than comparable steel shapes. Often this is not architecturally reasonable or acceptable to the client. Concrete may not be economical due to a building's overall size and/or shape. Incorporating the seismic provisions of Chapter 21 in the ACI 318-95 is needed to assure ductile performance of concrete buildings in a potential progressive collapse condition. However, detailing and constructing ductile concrete frames is very uncommon in many parts of the country. This could significantly affect a project cost or schedule, and the risk of contractor errors in reinforcing bar placement can be great.

Structural steel can be an excellent and economical material for mitigating progressive collapse. It was selected for use in a new Federal courthouse project in Laredo, Texas administered by the General Services Administration. The GSA requires all new government facilities to comply with recently developed security design criteria (General 1997). It directs the structural engineer to design new buildings for the loss of a column along the perimeter for the first two floors above grade without progressive collapse. Several framing system options were studied, and steel was chosen for the same reasons described in the above paragraph. The design approach and details used for this project are directly applicable to other buildings, regardless of the size or shape.

Figure 4 presents a typical floor framing plan for the court building project. One half of the building is four stories with a partial basement for underground parking, and the remainder is three stories beginning at grade. Floor heights vary from 15 to 22 feet in order to allow for high ceilings in the courtrooms. The site location is in south Texas which is governed by wind loading (negligible seismic risk). Architectural constraints prevented the use of bracing or shearwalls, and column sizes needed to be the smallest possible dimension. Square tube columns are exclusively used in the building to minimize the shape dimensions and eliminate weak axis buckling considerations. Except for five locations, it was possible to use 12 inch square tubes for this purpose. The architect's needs were met, and sufficient strength and stiffness requirements were achieved.

Exterior columns are the most vulnerable structural component for a terrorist bomb threat. Consequently, moment frames are placed around the entire perimeter. Interior moment frames are used in the areas above the underground parking. Although this is a controlled gated area, it can still be at risk of a terrorist bomb carried by an individual rather than a vehicle. Additional moment frame columns were added to limit the beam spans to about 30 feet. If a column were damaged in a blast, the maximum catenary span would not exceed 60 feet (generally considered to be the practical limit without requiring unacceptable beam depths). All moment frame columns are filled with high-slump, lean concrete to significantly increase its toughness in a bomb blast. The filled tube element is a very economical solution for strengthening the column against a close-in blast. A wide flange member would need much greater weight to develop similar toughness.

The moment frames serve two primary purposes. One is to provide overall stability and stiffness for lateral loads, and the other is to prevent progressive collapse of the floors if a column is lost (see Figure 2). For the moment frames to properly perform in a blast (i.e., beams deflect into a catenary and plastic hinges develop at the ends and midspan), the beam-to-column moment connections must reliably sustain large inelastic deformation under extreme overload and have the capacity to undergo large rotations without failing. The connection best able to satisfy these requirements is the proprietary SidePlate™ moment connection system shown in Figure 3. It has been thoroughly reviewed and tested, evaluated by ICBO (Evaluation Report No. 5366), and is extremely well-suited for this application (International 1999 and Houghton 1998). The connection was developed in response to the brittle fracture problems discovered in the "traditional pre-Northridge" moment connection which used complete penetration groove welds connecting the beam flange directly to the column flange. SidePlate™ connections use all fillet-welded fabrication, ductile weld configurations, and column tree/link beam erection sequence for increased quality control and cost efficiency (SidePlate™ 1999). The two full depth vertical plates connected to the columns by fillet welds accomplish moment transfer in a simple direct manner. These welds are ideally loaded in shear parallel to its longitudinal axis. Weld orientations like this are very ductile and can sustain large amounts of plastic deformation (Miller 1998). The SidePlate™ configuration also eliminates the need for internal diaphragm plates in any size tube or built-up box section since the beam is not directly connected to the column. An additional important feature is the connection's inherent ability to serve as an effective continuity element at a failed column location. The resulting catenary can span two bay lengths between the two columns located on either side of the failed column. Progressive collapse is prevented since the floors above can also span in a similar manner.

Arrangement of the moment frames for the courthouse project results in a series of simple, uniformly placed plane frames. The member sizes were initially sized in a conventional manner: (1) analyze the structure for gravity and lateral loads and (2) increase the stiffness, if necessary, to limit the building drift. The design was subsequently reviewed by a blast consultant. Slight increases in beam sizes were recommended after they performed a special blast pressure analysis.

Every lateral load resisting system has inherent strength capable of providing some degree of resistance to progressive collapse. When a structure is designed for large lateral forces, this capacity will naturally be greater. Therefore, it is reasonable to expect that the additional amount of structural hardening needed to mitigate progressive collapse will be less in high seismic/wind areas than for low seismic/wind areas due to the stronger lateral system already in place.

CONCLUSION

A discussion of blast explosions and the effect on conventional buildings was presented to familiarize the practicing engineer with concepts not often considered in design offices. An important objective of blast design is to prevent a catastrophic progressive collapse of the floors. Recommendations to mitigate progressive collapse in steel buildings were made and illustrated by examining the structural framing system and connection details of an actual project. It was shown that structural steel is a feasible and economical material for projects vulnerable to terrorist bomb explosions. The concepts and recommendations are directly applicable for use in other buildings.

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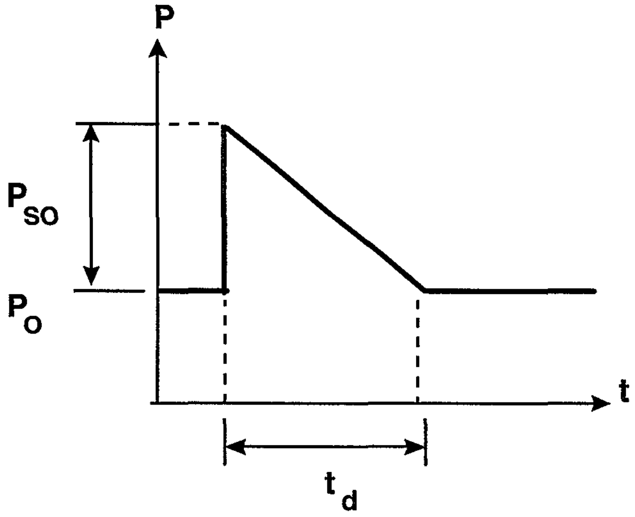
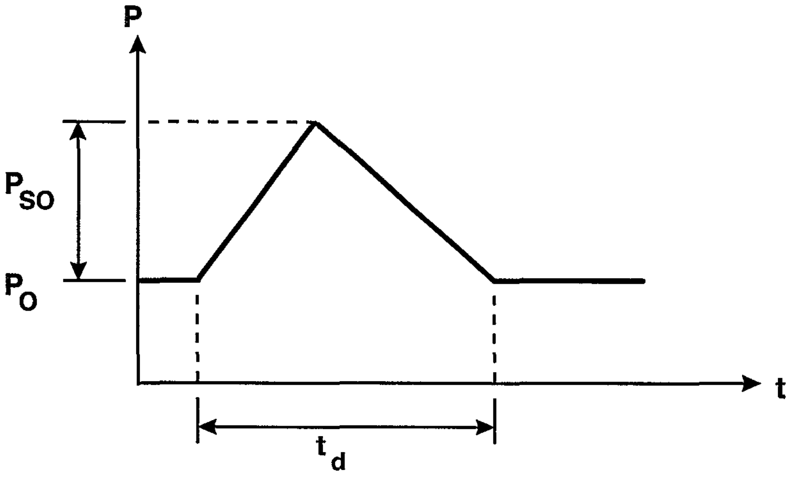
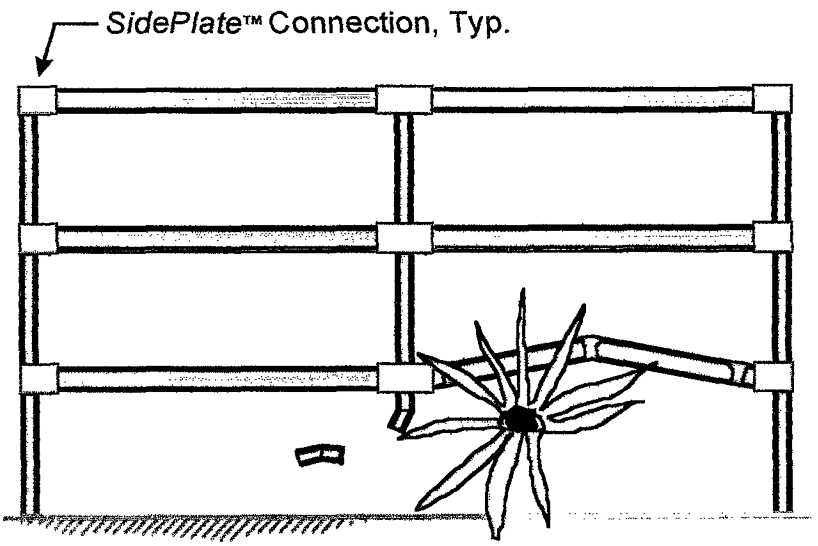


Shock Load

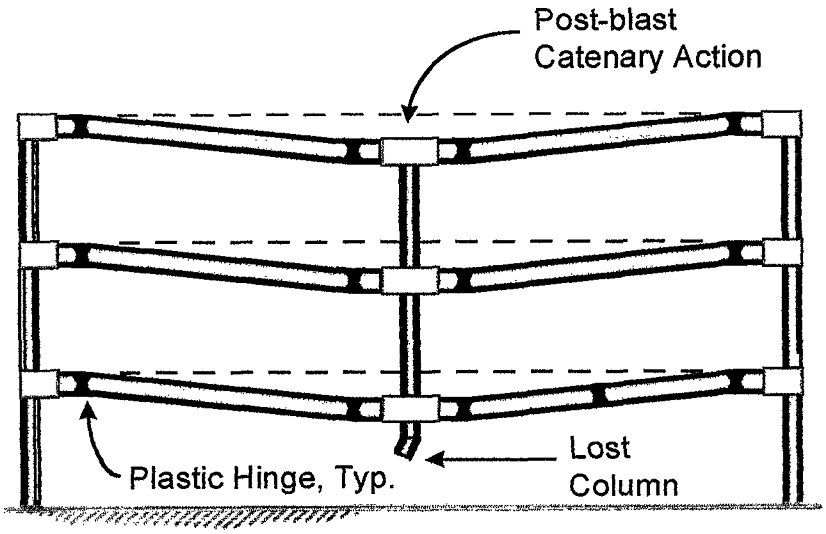


Pressure Load

FIGURE 1

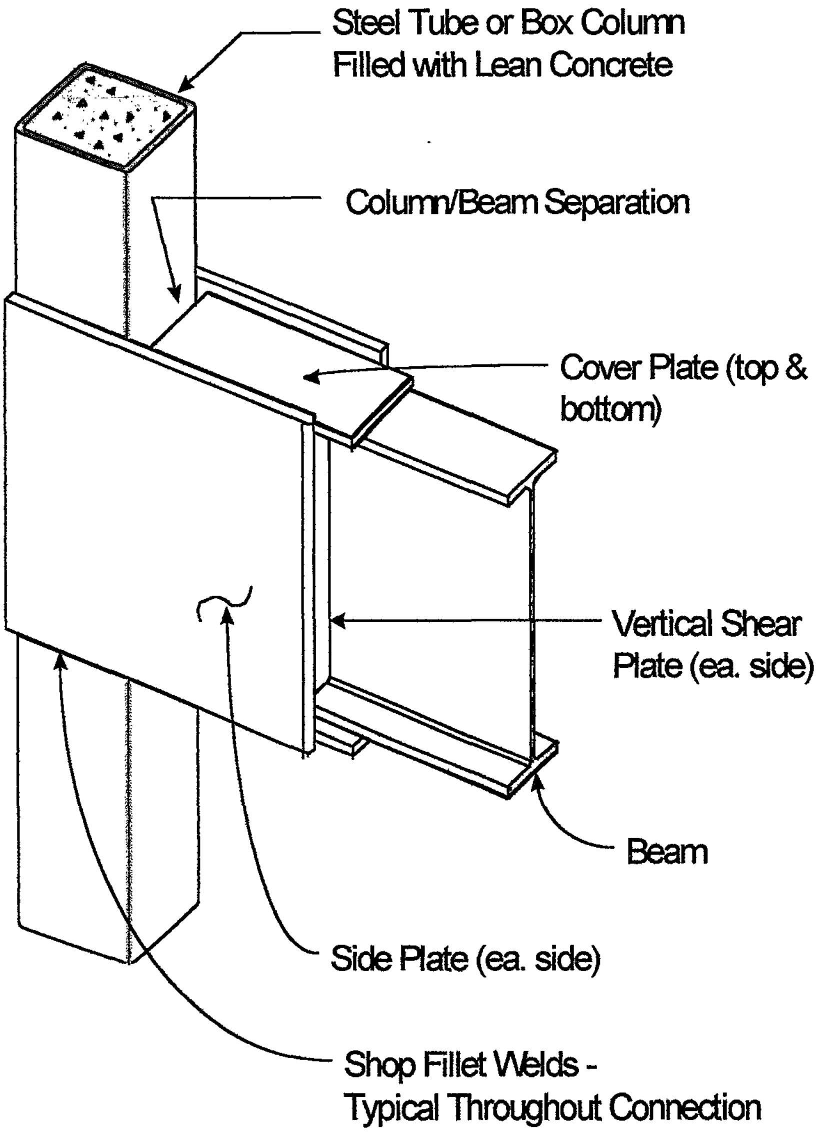


Explosion Event



Mechanism to Prevent Progressive Collapse

FIGURE 2



SidePlate™ Moment Connection

FIGURE 3

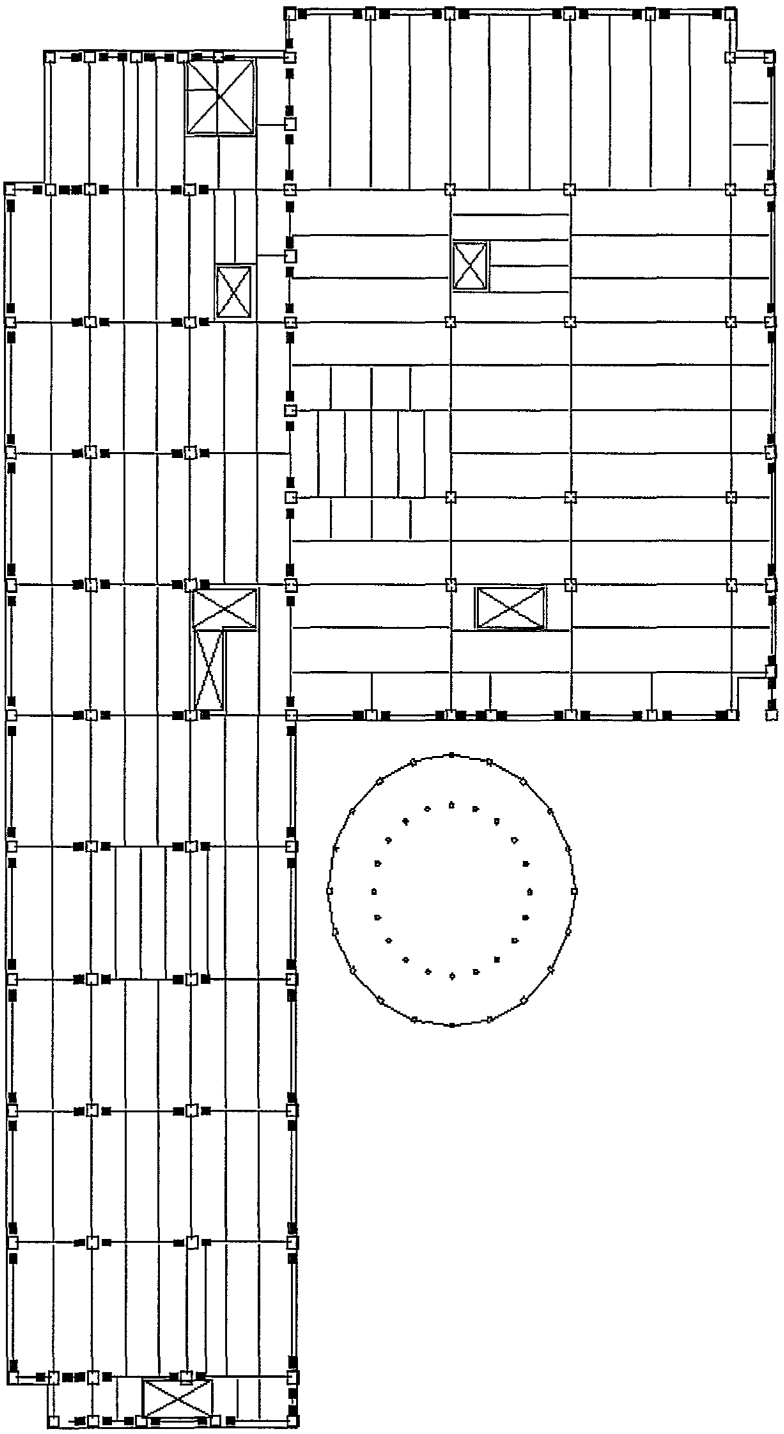
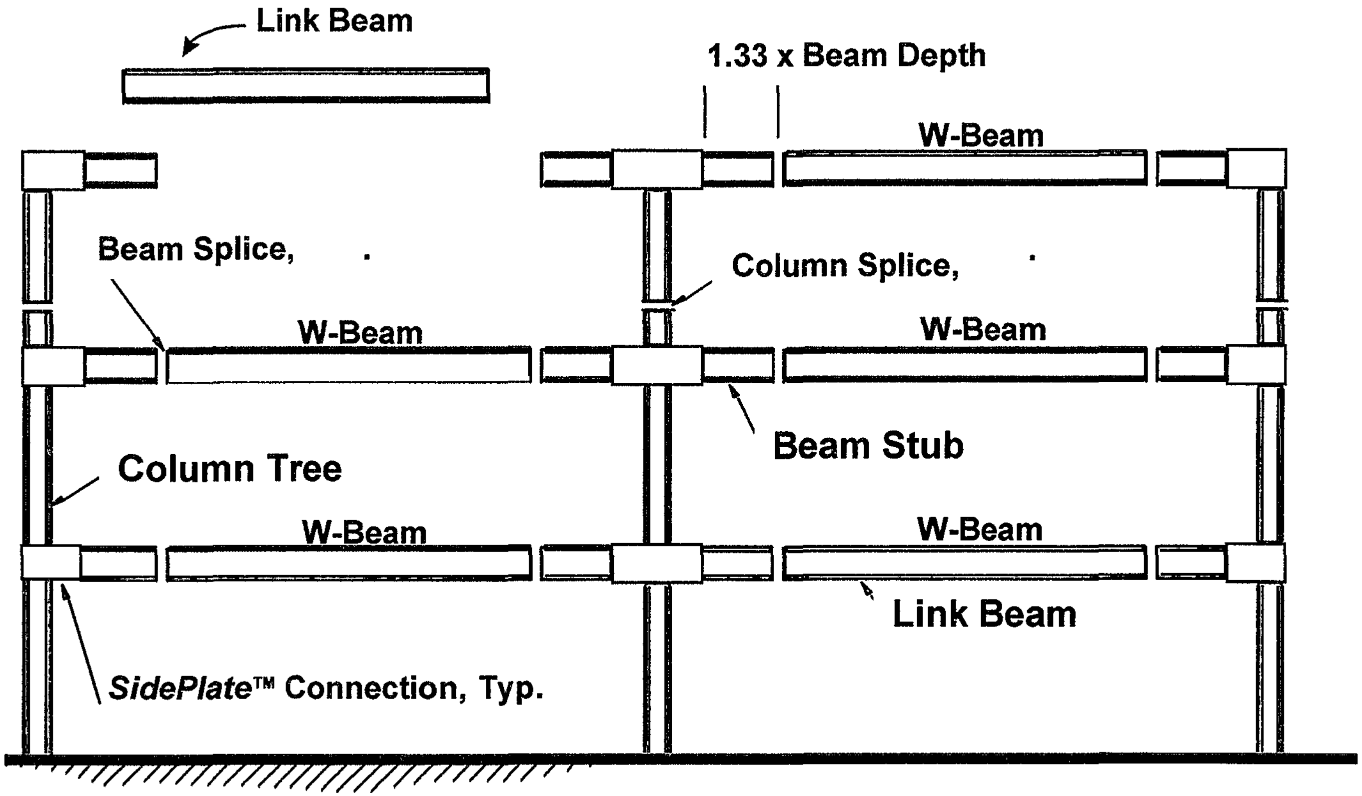


FIGURE 4



COLUMN TREE CONSTRUCTION

FIGURE 5