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Notes on Design Of Steel Parking Structures Including Seismic Effects

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This report presents information and tips on the design and construction of steel parking structures including information related to seismic behavior and design of such parking structures. Steel parking structures have been used throughout the world particularly in seismic regions such as Japan. This report is prepared to provide the state of the art knowledge of design of steel parking structures in general and particularly design of such structures in seismic regions. First, a summary of issues related to design of parking structures is provided. Then issues specific to design of steel parking structures such as design of deck systems, painting information, and fire resistance are discussed. Finally, notes on seismic design of steel parking structure are presented.

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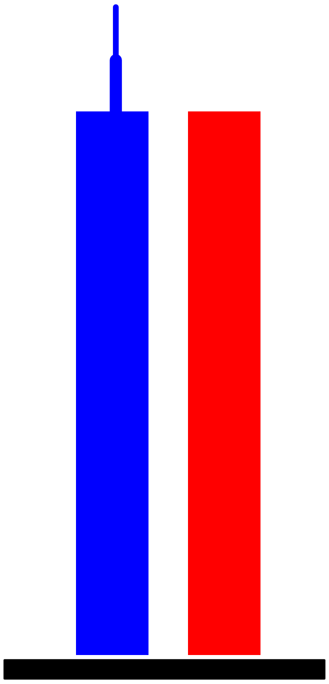

This report is dedicated to the memories of the firefighters and rescue workers who heroically sacrificed their lives on September 11, 2001 at the World Trade Center to save others and to the memories of all victims of this horrifying act of violence against innocents.

Lanny J. Flynn and Abolhassan Astaneh-Asl

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The opinions expressed in this report are solely those of the authors and do not necessarily reflect the views of the Chalker Putnam Collins & Scott, where the first author is a Principal and Vice President for Design-Build Services, the University of California, Berkeley where the second author is a Professor, the Structural Steel Educational Council, the American Institute of Steel Construction or other agencies and individuals whose names appear in this report.

NOTES ON DESIGN OF STEEL PARKING STRUCTURES-INCLUDING SEISMIC EFFECTS

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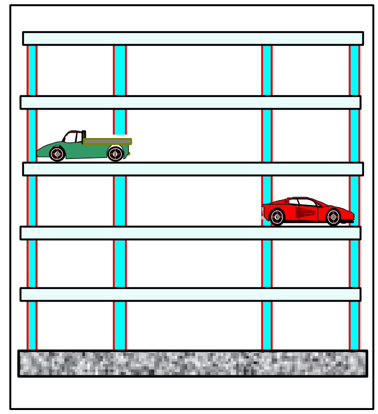
1. Introduction



1.1. Introduction

The need for multi-story parking structures has grown considerably over the years and will continue to grow as metropolitan densities increase. There are several key issues, which need to be addressed in the design of multi-story parking structures. They are:

1. Site considerations, environmental and neighborhood impacts and traffic access
2. Number of parking spaces, car circulations, ramps and other architectural aspects
3. Security and safety
4. Structural aspects (particularly in highly seismic areas, seismic design aspects)
5. Cost and speed of construction
6. Life cycle cost of maintenance
7. Fire resistance and/or need for fireproofing.

The first three items in the above list, to great extent, are impacted by the decisions of architects. Items 4 to 6 in above list, also are impacted by architectural aspects, however, these three items are primarily impacted by the structural design and decisions made by the structural engineers. Today, structural steel provides viable systems that address the above key issues. In the past, a large percentage of parking structures throughout the country were designed and built using reinforced concrete structures. However, since 1980's in many regions of the US including seismic areas such as California, more and more steel parking structures have been designed and built. According to Emile Troup (1989), nearly three out of every five car parks for which contracts were awarded in 1987 in New England were steel. He attributes this increase in use of steel structures in open parking structures to the fact that as a result of research and testing done in 1970's the issue of fire-proofing of steel structures in car parks was put to rest and the use of "unprotected steel" in parking structures was accepted (Troup, 1989). Because of extensive research and testing of bare steel structures subjected to fire, the fire codes no longer have very stringent requirement for fire protection of steel car parking structures. This development, along with education and dissemination of information on viability and economy of using steel structures in car parking, may have been instrumental in visible increase in design and construction of steel parking structures.

1.2. General Aspects of Design of Parking Structures

Design of car parking involves good combination of information on not only building design but also bridge design. Like bridges, in many cases, especially in open car parks, there are very few non-structural elements and the car park building, as a bridge is primarily a bare structure with minimal mechanical and non-structural elements. According to Emile Troup: " In many cases the structure – the deck and frame – *is* the car park. The concept and design of the deck and frame will largely determine the success of the facility: its cost and its ability to perform, relatively problem free, for the design life expectancy. Therefore, it is recommended that the structural engineer for the car park share the lead role as building designer, in close association with others charged with developing the optimum parking concept." The April 2001 issue of the *Modern Steel Construction* magazine (MSC, 2001) featured six articles on various aspects of steel parking structures. In almost all case studies, the prominent role of structural engineer and the impact of structural engineering decisions on making the projects highly successful are very clear. The reader is urged to refer to the articles for very useful information and case studies on efficient design and construction of modern steel parking structures.

As an introduction to design concepts for parking structures, the following briefly lists the important requirements:

- Since floor loadings are relatively light, floor plans usually need large, simply framed areas ordinarily consisting of easy-to-design structural elements.

- The size and number of columns in parking structures is critical since closely spaced and large columns quite often reduce the useful width of the traffic lanes as well as reducing width and number of the parking spaces in a given floor. Therefore, parking structures normally have clear spans of about 60 feet at least in one direction.

- Because both framing and floors are atmospherically exposed, this exposure may create a condition of standing water and in some areas exposure to de-icing salts. Hence, long-term structural maintenance should be given appropriate care and consideration. Joints in the floor decks can result in leakage, corrosion and chloride attacks. Floor joints should be avoided if possible and if they are absolutely needed, the number of joints in the floor deck should be kept to a minimum.

- Although gasoline and other combustible elements are invariably present and thereby suggest fire hazards, this is not the case in open deck parking structures. Tests have determined that this building type needs no fire protection since 1) fire-spread risk is minimal, and 2) if an incendiary situation does start it is easily accessible to fire-fighting devices. It should be noted that very useful information on this and other items regarding fire safety of steel structures could be found in just published book by A. Buchanan (2001).

- For a self-standing parking structure, foundation, architectural, and mechanical costs are relatively minimal, and largely, structural elements are approximately two-thirds of the total construction cost of this building type.

- Low construction and life-cycle costs and speed of construction are primary objectives of this building type.

- In many urban parking structures, the architects and owners demand a quality product that fits the upscale architecture of their surrounding areas and adjacent buildings. Since in most parking structures, the structures are mostly exposed, the close coordination of the architectural and structural aspects becomes a necessity to achieve an aesthetically pleasing, structurally sound and economical parking structure.

- Quite often in urban areas, the lots available for parking structures are tight in space and have limited construction-launching space. Therefore, the structural system should lend itself to relatively small amount of on site construction activity and more to shop pre-fabrication.

One of the primary goals of this publication is to provide information to architects, engineers, and owners, on the design and construction of steel frame open deck parking structures in general and particularly in seismic regions. After introduction in Chapter 1, since in many open deck-parking structures, the steel structure is exposed, Chapter 2 is devoted to painting issues. Chapter 3 summarizes current fire code requirements for steel open deck parking structures. Chapter 4 of the report discusses issues related to design, construction and maintenance of parking floor slabs. Chapter 5 is devoted to discussion of issues related to seismic design of parking structures and pros and cons of currently used steel structural systems when used in a steel parking structure. A list of references is provided at the end of the report.

2. PAINTING GUIDE

2.1. Introduction

This chapter is intended to provide guidance for architects, engineers, owners, or specifiers that will assist them in making proper choices in selecting a protective coating system for the structural steel for a parking structure.

2.2. Factors That Affect Cost and Performance

When selecting a coating system, the system sought should provide maximum performance at the lowest cost. In making the proper choice, a number of factors should be considered:

- Functional requirements;
- Service life of coating and structure;
- Quality of coating system;
- Quality of surface preparation and application;
- Maintenance program; and
- Determination of coating cost.

2.2.a. Functional Requirements

In most environments, coatings are a requisite for the protection of steel from corrosion. Usually exposed steel in parking structures is quite visible to the public; hence, maintenance of its appearance – the gloss and color retention – is an important requisite.

2.2.b. Service Life of Both Coatings and Structures

One of the dependencies that influence the selection of a coating system is the length of time the coating provides the corrosion protection and the maintenance required. With present-day coating systems, the usual expectation for paint life is from 20 to 25 years.

2.2.c. Coating System Quality

As previously noted, the type of coating selected is an important factor for both its performance and cost. Normally, the material is from 15% to 20% of the system's total cost. Thus, merely saving a few dollars-per-gallon for lesser quality materials may not be a wise decision.

2.2.d. Quality of Surface Preparation and Application

In virtually all systems that use high-technology coatings (e.g., ethyl silicate; zinc-rich, epoxy-polyamide polyurethanes), their most costly portion is surface preparation. The degree of surface preparation that is reached is a critical factor in determining ultimate performance of the coating system. Table 2.1 summarizes methods of surface cleaning.

A recognized necessity for high-technology coating is blast cleaning. Hence, by initially investing in a superior surface preparation, the result will usually be a lifetime increase. Usually an SSPC-SP6 commercial blast cleaning, or an SSPC-SP10 near-white metal blast cleaning, is recommended for use in parking structures.

The following is a brief of SSPC-SP-6 and SSPC-SP-10 blast cleaning:

a) *SSPC-SP 6 "Commercial Blast Cleaning"*

This method defines a more thorough, but not perfect, degree of blast cleaning. It is a minimum specification that is used with coating systems of higher performance, yet less forgiving of surface imperfections.

During cleaning, all rust, mill scale, and other detrimental matter is removed; however, staining that resulted from previously existing rust and mill scale, is permitted on 33% of each square inch of surface. The advantage of commercial blast cleaning lies in the lower cost for adequate surface preparation for a majority of cases where blast cleaning is deemed appropriate.

Note that certain paint systems (e.g., inorganic zinc-rich), may not be able to tolerate placement over a surface that has been prepared in this manner.

b) *SSPC-SP 10 "Near-White Metal Blast Cleaning"*

While this specification's price is higher than the "Commercial", it only permits staining on 5% of each square inch of the previously described surface. Generally used, only when the expense of this higher cleaning level is justified by the chosen paint materials, and the severity of the anticipated service environment; Near-White Metal Blast Cleaning is frequently specified in combination with inorganic zinc-rich coatings.

Unless the anticipated service environment is extremely severe – unlikely in the case of parking structures – the advantage of this type of cleaning can be considered as optimum performance achieved at 10% to 35% savings in surface preparation costs over that of SSPC-SP 5 "White Metal Blast Cleaning."

It is not anticipated that any parking structure will require the use of a surface preparation that is more stringent than the "Near-White Blast Cleaning."

2.2.e. Maintenance Program

The magnitude of maintenance expenditure and the interval between such expenditures depends on the initial coating choice and the established type of maintenance program. A well-established maintenance program will help create a substantial increase in the life of the initial coating system.

2.2.f. Determining Coating Costs

To assist in making an informed decision, designers, specifiers, and owners of parking structures, should require information on comparative costs and lifetime extents of alternative coating systems. Shop-application coating costs are normally divided as follows: material, surface preparation, application, inspection, and overhead. For precise estimates, individual shops should be contacted in order to determine the costs of labor, materials, and other items for specific coating systems.

2.3. Recommended Coating Systems for Parking Structures

1. SSPC-SP 6, 2-pack epoxy polyamide zinc-rich with high-build epoxy topcoat.
2. SSPC-SP 6, followed by moisture-cured polyurethane zinc-rich primer and Aliphatic polyurethane acrylic topcoat.
3. SSPC-SP 10, followed by ethyl silicate inorganic zinc primer and epoxy topcoat.
4. SSPC-SP 10 / epoxy-polyamide zinc-rich, high-build epoxy topcoat.

NOTE:

1. For these systems, an Aliphatic polyester polyurethane topcoat may be substituted in order to attain improved a) durability, b) abrasion resistance, and c) easy removal of graffiti.
2. For slip critical connections surfaces an AISC Class B surface, conforming to SSPC-PS-12.01 can be provide by most paint manufactures.

LOW-VOC ALTERNATIVES – VOC = 2.8 lbs / gal (340 g / liter)

To meet future 2.8 lbs / gal VOC (340 g / liter) requirements the above-listed Systems 1 through 4, plus the alternate Aliphatic polyurethane topcoats are available for commercial use at this level.

NOTE: Low-VOC versions of these coatings do not have the long service life that has been documented for their high-VOC counterparts, therefore, the manufacturer/supplier should be required to furnish evidence of both their field performance and application properties.

Where water-borne coating systems are required, the following can be specified:

SSPC-SP 10 followed by water-borne inorganic zinc alkali silicate primer with 100% acrylic topcoat.

NOTE: While this system has demonstrated a good long-term service life, the manufacturer/supplier must demonstrate the suitability of shop application properties, as well as citing the product's specific field-usage.

2.4. Specifying Coating Systems

System 1: Epoxy Polyamide

- Zinc-rich epoxy primer; SSPC-Paint 20, Type II
- Epoxy intermediate or topcoat: SSPC-Paint 22.
- Polyurethane topcoat (optional). SSPC specification is not available for this. Request supplier to submit laboratory and field-test data. This topcoat must consist of two-component Aliphatic isocyanate polyurethane.

System 2: Polyurethane/Polyurethane

- Moisture-cured polyurethane zinc-rich primer. SSPC-Paint 20, Type II. Request paint supplier to submit exterior exposure test panels or service) data for at least three years; names of the facility owners should be given to verify the performance.
- Epoxy intermediate is optional.
- Polyurethane topcoat.

System 3: Inorganic Zinc-Epoxy

- Ethyl silicate inorganic zinc-rich primer; SPC-Paint 20, Type I.
- Epoxy intermediate or topcoat.
- Polyurethane topcoat (optional).

System 4: Epoxy/Epoxy

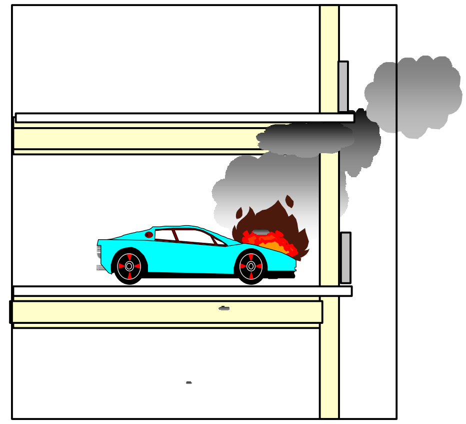
- Epoxy polyamide zinc-rich primer SSPC-Paint 20, Type II. Request paint supplier to submit exterior exposure (test panels or service) data for at least three years; names of the facility owners should be given to verify the performance.
- Epoxy intermediate or topcoat (see System 3).
- Polyurethane topcoat (optional; see System 3).

Table 2.1

SUMMARY OF SURFACE PREPARATION SPECIFICATIONS

SSPC Specification	SSPC-Vis 1-89 Photograph	Description
SP 1, Solvent Cleaning		Removal of oil, grease, dirt, soil, salts, and contaminants by cleaning with solvent, vapor, alkali, emulsion, or steam.
SP 2, Hand Tool Cleaning		Removal of loose rust, loose mill scale, and loose paint to degree specified, by hand chipping, scraping, sanding, wire brushing, and grinding.
SP 5, White Metal Blast Cleaning	A, B, C, D, SP 5	Removal of all visible rust, mill scale, paint, and foreign matter by blast cleaning by wheel or nozzle (dry or wet) using sand, grit, or shot. (For very corrosive atmospheres where high cost of cleaning is warranted.)
SP6, Commercial Blast Cleaning	B, C, D, SP 6	Blast cleaning until at least two-thirds of the surface area is free of all visible residues. (For rather severe conditions of exposure.)
SP 7, Brush-Off Blast Cleaning	B, C, D, SP 7	Blast Cleaning of all except tightly adhering residues of mill scale, rust, and coatings, exposing numerous evenly distributed flecks of underlying metal.
SP 8, Pickling		Complete removal of rust and mill scale by acid pickling, duplex pickling, or electrolytic pickling.
SP 10, Near-White Blast Cleaning	B, C, D, SP 10	Blast cleaning nearly to White Metal Cleanliness, until at least 95% of the surface area is free of all visible residues. (For high humidity, chemical atmosphere, marine, or other corrosive environments.)
SP-11-89T, Power Tool Cleaning to Bare Metal		Complete removal of all rust, scale, and paint by power tools, with resultant surface profile.
Vis 1-89, Visual Standard for Abrasive Blast Cleaned Steel		Standard reference photographs; optional supplement to SSPC Surface Preparation Specification SSPC-SP 5, 6, 7, and 10.
Vis 2, Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces		A geometric numerical scale for evaluating degree of rusting of painted steel, illustrated by color photographs and black and white dot diagrams.

3. FIRE CODE REQUIREMENTS



3.1. Fire Code Requirements

Recent years have witnessed appearance of an increasing number of open-deck, multi-level parking structures that have unprotected steel framing. This growth of unprotected steel framed open-deck parking structures is in recognition that fire severity in this type of structure is actually quite low.

The American Iron and Steel institute (AISI) and the Municipal Parking Congress conducted research in order to provide a new, statistically reliable basis for evaluating the fire protection requirements and the insurance rates of parking structures. To accurately document an actual fire severity and its effects on parking decks, an intensive study was conducted in Scranton, PA on 15 October 1972. In this study, AISI sponsored a full-scale fire test using a newly erected, multi-level parking structure. This full-scale fire test was conducted while the facility was in normal daytime operation.

The principal objective of AISI was to make a comprehensive and totally objective determination of the effects of a burning auto on bare structural steel framing. During this 50 minute test period the maximum recorded steel temperature on a steel girder, located directly above the burning auto, was 440° F. Within the same test period, this girder showed a maximum deflection of 1 5/8” and a maximum elongation of 1/8”. After the completion of the test, both the deflection and elongation readings returned to zero.

All the results and findings of this full-scale test were documented in detail. The resulting data confirmed the fact that bare-steel framing in open-deck parking structures faces little danger from automobile fires.

Model building codes reflect these carefully observed findings by allowing the use of structural steel without fireproofing or specific fire projection assemblies for open-deck parking structures. Table 3.1 shows a short summary of the requirements of two model-building codes commonly used along the west coast. The allowable height, number of tiers and area are a function of many factors. The applicable building code should be consulted for detailed requirements.

Special considerations should be given to open parking structure applications where the building code requirements mandate that some or all of the structural steel have fire-resistance ratings. Most manufacturers of steel fireproofing materials have products for this application. Following the specific recommendations of the manufacturers is essential for determining the proper product application. Factors that should be considered when selecting a fireproofing system are:

a) Climate/Exposure: The very nature of an open parking structure requires the fire-protection material to have a measured resistance to environmental effects. This would include: freeze-thaw cycling, direct rain exposure, corrosion protection and wind erosion. Most manufacturers have specific tests that document their products' performance under these conditions. Additionally, UL fire testing often lists particular products for exterior exposure applications.

b) Durability: In addition to environmental exposure, open parking structure applications are susceptible to the normal activities of the building's use. This may involve such things as human contact and vehicular impact. Typically, manufacturers can provide density, hardness, and impact-resistance testing, in order to verify their products' ability to stay in place when abused.

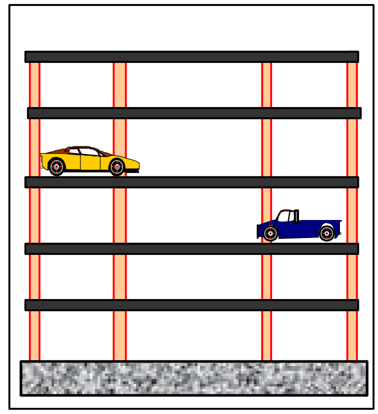
Table 3.1

HEIGHT AND AREA LIMITS IN MODEL BUILDING CODES FOR OPEN DECK PARKING STRUCTURES OF UNPROTECTED NONCOMBUSTIBLE CONSTRUCTION

Code	Edition	Number of Tiers and Area per Tier Allowed by Codes
IBC International Building Code	2000	Eight Tiers @ 50,000 ft^2 without an automatic sprinkler system. Additional tiers and area per tier are allowed by the IBC if certain provisions are met. For example, a Type II-B parking structure with all sides open may be unlimited in area when the height does not exceed 75 ft. See Note (a) below.
ICBO Uniform Building code	1997	Eight Tiers @ 30,000 ft^2 without an automatic sprinkler system. Additional tiers and area per tier are allowed by the UBC if certain provisions are met. For example, a Type II-N parking structure with all sides open may be unlimited in area when the height does not exceed 75 ft. See Note 9a) below.

(a) For more information on these code provisions and their proper use, the reader needs to refer to the actual code ((ICC, 2000) and (ICBO, 1997).

4. SLAB DESIGN CONSIDERATIONS



4.1. Introduction

Structural steel is the basic framing structure material for many open deck-parking buildings. Concrete is usually used as structural floor material. Many concrete floors supported by both structural steel and concrete frames in the past often have required either complete removal or extensive repair. Therefore, special attention needs to be paid to design and construction of floor system in an open parking structure. The floors in an open parking structure are expected to be subjected to wet and corrosive environment. Unlike closed human occupancy floors where minor hair cracks in the floor are normally tolerated, in car parking, such cracks can be the source of leakage as well as corrosion. In recent years, through development and use of epoxy coated rebars, galvanized composite steel decks, post-tensioned concrete floors and special deck coating, the life expectancy of parking floors have been extended significantly and the maintenance problems have been reduced to normal expected maintenance. In addition, unlike building structures where flat floors are most desirable, in a parking structure, quite often, the floors need to have slope to rapidly drain the water.

Today, one of the most economical floor systems for steel parking structures is typical cast-in-place composite steel deck/concrete slab system connected to the floor steel beams and girders with shear studs. The resulting floor makes floor beams and girders composite members as well. Pre-cast or cast in place concrete slabs have also been used for parking floors. In case of cast in place slabs, post-tensioning of slab has been used (Monroe and Baum, 2001) to have a relatively large joint-free and crack free floor avoiding leakage problems that can occur in pre-cast concrete floors. To ensure long term durability of reinforced concrete decks and to avoid corrosion, the use of epoxy-coated.

In seismic areas, the use of steel deck and concrete slab is preferred over cast-in-place or precast systems. Recent tests by Astaneh-Asl et al. (2001) has indicated that the steel deck provides a very ductile secondary system to carry the floor loads, in a Catenary manner, even if a column has collapsed or removed.

In recently completed parking, structures in New York and New Jersey designers Englot and Davidson (2001) have used precast/prestressed double tees for flat portions of the structure. The designers indicate that the lighter weight double tee floor construction along with steel framing system has resulted in overall lighter structure, longer spans, less number of columns and foundations and less seismic forces. The reduction of seismic forces was very important for this structure since the site had a thick layer of seismically liquefiable organic soil. In addition, the double tee floor system has resulted in less overall depth of floors providing generous headroom of 8'-2" to the bottom of the pre-cast concrete double tee beams. For ramps, which were double helical, external ramps, high-strength (7000 psi in 28 days) cast in place reinforced concrete slabs were used Englot and Davidson (2001). Fly ash, silica fume, a corrosion inhibitor and a high range water reducer were included in the mix to ensure long life for the ramps.

The concrete in the slab can be normal weight or lightweight concrete. From seismic point of view, of course lightweight concrete is preferred. This is because of lightweight concrete's lower weight (mass) resulting in smaller seismic forces to be dealt with in design. Performance of lightweight concrete and structural members using lightweight concrete has been studied and tested in recent years and significant information on this subject is currently available in ACI and other publications.

One of the early applications of lightweight concrete deck was in the upper deck of the San Francisco Oakland Bay Bridge in 1936. The lightweight slab has been under heavy traffic (currently with a daily traffic of about 50,000 trucks and 250,000 cars). After the 1989 Loma Prieta quake, as part of comprehensive studies of the Bay Bridge, (Astaneh-Asl et al., 1990-1992) the second author led a study to assess the condition of the light weight concrete deck (Astaneh-Asl and Mori, 1990). The studies indicated that the lightweight concrete deck has performed well and the concrete did not show any sign of deterioration, even though it was exposed to over-water environment and heavy traffic.

4.2. Slab Construction for Open Deck Parking Structures

4.2.a. Slab Design Characteristics

Typically floors in steel-frame, open deck parking structures consist of reinforced concrete slabs. In recent years, a number of modern parking structures have been constructed in California and other areas using typical steel deck concrete slab system. A parking structure deck is less dependent on its supporting structural frame, than on the slab materials and the construction details. Over economizing floor slabs should not be a controlling design factor in parking structures. The designer should remember that the parking slab is the structural element that is most frequently subjected to wear and most often exposed to harsh atmospheric elements. Virtually every square foot of parking structure surface is a source of income and owners are usually unhappy when they have to shut down for slab repairs.

Durability is a primary design consideration for parking structures. Surveys have revealed that structural slabs and their topping deteriorate a good deal prior to their supporting structural frames therefore it is strongly recommended that the designer provide sufficient attention in the design and detailing of the parking slab decks. This chapter describes current practice that will help obtain satisfactory concrete slabs for decks that are supported on steel frames.

4.2.b. Service Loads

1. *Dead Loads*

Normal weight stone concrete with a density of about 150 pcf, is the most common and is often recommended for its high level of durability. Lightweight aggregate concrete, with a density of about 110 pcf, have also been used successfully in the past and if properly designed and detailed can meet the durability requirements for parking decks. More information on design and details are provided in Section 4.3.

2. *Live Loads*

Most national building codes specify a uniformly distributed, minimum live load of 50 pounds per square foot (psf), or a minimum concentrated load of 2,000 pounds that is placed anywhere it will produce greater stress.

3. *Snow and Other Roof Loads*

If the top parking deck is not covered by a roof structure snow loading should be accounted in applicable geographic locations. Snow loads should include drifts along parapet walls, sides of exposed autos, etc. to the extent required by the local code. Deliberate snow piling to clear parking spaces is a common practice that should be investigated. Such snow loads may be considerably higher than those in the uniformly applied code requirements.

4. *Internally-Induced Stresses*

Volume changes that result from a) thermal, b) shrinkage, and c) creep effects can cause indirect forms of service loads on all slabs. These loads must be accounted for in the design of any rigidly attached steel frame element. In addition, if a post-tensioned slab system is used effects from elastic shortening of the slab must be investigated.

Internal stresses are reduced and better managed by utilization of appropriately spaced expansion joints, and construction joints – such as pour strips. However, some degree of stress is always present.

5. *Loading Variations*

Usually, concrete slab design and construction is regulated by the ACI Code. Pre-stressed concrete must be designed by following the procedures required by the ACI Code's "strength design" method (formally referred to as *ultimate strength design*); the working-stress design method of ACI Code's Appendix A, may only be used for non-prestressed concrete.

4.2.c. Concrete Qualities

1. *Basic Materials*

Concrete's quality is dependent on four aspects: a) its materials, b) mixture, c) placement procedures and d) the curing process. In building a slab system, if care is used in all steps except the use of high-quality concrete, the parking deck slab will present a problem. It is not costly to achieve concrete of high quality. It does however, require effort since several choices and project participants are involved in its preparation and placement.

The first step in the design of the slabs is to specify the quality of the requisite materials that make up the concrete.

a) Stone aggregate concrete of normal weight is a desirable material for parking structures in consideration for their weather exposure however, lightweight aggregate can be used.

b) The ACI Code (Reference 6) specifies acceptable basic materials for concrete, and refers to its Commentary, the Code of Practice, and the national standards of the American Society for Testing and materials (ASTM).

ACI Code Chapter 3 lists materials, Chapter 4 stipulates durability requirements, and Chapter 5 specifies the means that will assure concrete's proper quality.

In order to obtain the correct concrete for every planned project, using these code provisions is a prerequisite.

2. *Externally-Applied Chlorides*

The nation's highways and city streets are often kept free from accumulation of snow and ice by extensive use of chemicals such as de-icing salts. Chlorides can readily penetrate and damage the contacting concrete structure if both concrete and its steel reinforcement are improperly designed and constructed.

Parking structures that do not employ chlorides on interior floors are still subjected to roadway salts by autos entering for parking after being driven on chloride-treated roads. Therefore, parking structure floors that are not directly exposed to the weather are also subjected to the problem of roadway salts.

When *externally applied chlorides* are placed in direct contact with the slab, three added constraints are required by the ACI Codes:

- A maximum water/cement ratio is stipulated

- A minimum entrained-air content is required

- A minimum clear, concrete cover on reinforcing is specified.

3. *Permeability Reduction by Minimizing Water-Cement Ratio*

Concrete should be made as impermeable as is possible when the parking structures are frequently exposed to de-icing salts. Consideration should be given to the ratio between water and the cement materials of the concrete. This should be decreased as much as practicable. The ACI Code stipulates a maximum water-cement (w/c) ratio for different conditions and exposures.

4. *Admixtures with Normal Concrete*

Concrete ingredients that are beyond the basic aggregates – cement and water – are classified as admixtures that require particular formulation under the supervision and approval of the structure's design engineer.

Some admixtures can be very beneficial; or are mandatory for certain structures to meet the ACI Code. Others, even though offering convenience during construction, can be harmful to the concrete in the long run, and are either prohibited or not recommended. An admixture should be avoided unless it serves a specific purpose in a particular structure. The indiscriminate use of admixtures is not advisable. .

5. *Air-Entraining Admixtures*

A simple description of air entrainment is the process of chemical capture and maintenance of microscopic air bubbles within a fluid concrete mixture, as well as after the concrete has set. These bubbles behave as tiny pressure relief valves in the process of carrying out their major functions:

a) Enabling the concrete to help withstand freezing-thawing cycles
b) Enabling the concrete to help withstand scaling action of de-icing salts on its surface.

Air entrainment is recommended for all exposures of parking structure slabs since it improves both workability and surface finish.

For areas subjected to freeze-thawing conditions, and/or where de-icing salts may reach the slab, the ACI Code (Section 4.1.1) requires air-entrainment.

Air-entrainment is required in varied amounts ranging from 4½ to 7½%; a particular amount is given for each of the exposures listed in ACI Code Table 4.2.1 and described in the ACI Code Commentary.

Air entrainment makes a significant lessening of bleed water. As a result, concrete finishing can therefore be started sooner, and the long-term quality of the surface is improved.

6. *Water-Reducing Admixtures*

By reducing the water content necessary for the production of a workable concrete, such admixtures can radically alter both fresh and the post-hardening properties of the concrete. The following are achievable goals that may be gained from this admixture type:

- Reduction of water/cement ratio
- Increase slump and workability
- Reduction of water amount needed to produce a particular slump

Normal water-reducing admixtures provide a 5 to 10% water reduction. A high-range extension of this admixture type, called a *super-plasticizer*, can reduce water content by 12 to 30%, producing a flowing concrete, which remains cohesive. When using a super-plasticizer, another means of specifying a water/cement ratio standard of quality will be necessary.

The possible advantage of using any water-reducing admixture for parking structure slabs is the ability to reduce the concrete's water/cement ratio and permeability while still providing a workable mixture. Careful vibration and consolidation of the concrete particularly around the reinforcing steel is required and should not be neglected when any water reducer is used.

7. *Mineral Admixtures*

Over a period of many years, several classes of finely divided admixtures have been used in producing concrete. They consist of blast furnace slags and other minerals that have cementitious properties and pozzolans (siliceous materials) that can improve certain concrete qualities and become cementitious. Fly ash, a by-product of coal-burning power plants, is an example of the latter effect.

8. *Microsilica Admixture*

Microsilica is a brief substitute as a name for *condensed silica fume*, a by-product of alloy steel production. The particles of this element are ultra-fine in size and are marketed in either powder or liquid form.

Microsilica benefits parking structure slabs as compared to ordinary concrete by reducing the permeability and reducing the chloride intrusion.

Fresh concrete that contains microsilica, will behave in a manner quite different from that of ordinary concrete. In adding microsilica, contractors should be given notice for radical changes in normal mixing, slump, placing and finishing habits, and the need for strict adherence to the microsilicia manufacturer's recommendations for handling this type of concrete.

In order to place a microsilica-enhanced concrete slab, it is usually needed to utilize a compatible super-plasticizer, i.e., a high-range water-reducing admixture.

9. *Corrosion-Inhibiting Admixtures ('Inhibitors')*

Because of its very high, natural alkalinity, concrete imparts a protective oxide film on the embedded steel. This film is penetrated or broken down by certain aggressive chemicals such as chlorides which can start steel corrosion.

Admixtures such as calcium nitrite can stabilize and reinforce the protective film when it is attacked. The amount inhibitor will vary directly with the amount of attacking chloride present in the concrete. Steel corrosion will begin when the level of chloride exceeds the 'inhibitor's' ability to maintain the film. These admixtures will delay both the start and rate of steel corrosion and are effective if the chloride intrusion does not increase more rapidly than originally estimated.

10. *Placing, Finishing, and Curing Concrete Slabs*

In order to attain quality concrete at the job site the following is a listing of *do's* and *don'ts*:

a) Use the lowest possible slump consistent with conditions of the given job; plan for a water-reducing admixture if needed for maintaining the specified low water/cement ratio.

b) Do not add any water in the field beyond the design mix dosage. Reject watered-down mixes.

c) Despite the use of plasticizers, mechanically consolidate the concrete particularly around all embedded materials. Avoid excessive vibration, which among other effects can cause segregation of aggregates, surfacing of water and the reduction of air entrainment.

d) Make certain that the concrete is well compacted under the top layer of reinforcing steel to avoid steel settlement during the concrete's hardening. Concrete placed over settled bars is weak and can crack as a result.

e) When using a microsilica admixture, be certain that you have learned the proper techniques for handling this concrete type.

f) Do not begin trowelling the concrete surface until the bleed water has evaporated. A high water/cement ratio at the surface with less durable concrete can result.

g) If possible, use *wet curing*. A *curing compound* should *not* be employed unless there are some very good supportive reasons.

4.3. Slab Joint Details

Open deck parking structures are more directly affected by weather-temperature changes than any other occupied building type. Since the parking structure has no roof insulation, and no exterior wall, its entirety is subjected to the full range of exterior temperatures.

Expansion joints should be built into parking structures in order to accommodate the thermal changes. Control and construction joints may also be needed in slabs between the expansion joints in order to control either cracking or the size of a day's work.

All of the joints in the slab should be designed to withstand the effects of vehicular traffic. Since the parking structure is not subjected to highway or bridge stresses, its joints can be designed simpler and more economical. Unless completely drained, every slab joint of this structure should be watertight, and capable of long-term maintenance.

Requirements for slab expansion joints are related to volume change therefore the shorter the distance between slab joints, the less movement or intermediate cracking will occur. Weighed against frequent joints is the cost to properly build and maintain them.

1. *Joint Types*

Every parking structure requires three types of slab joints:

a) *Expansion Joint*

This joint will adjust to temperature changes that surround the building throughout its existence. Expansion joints accommodate the overall structure's expansion and contraction and divide it into distinct parts; sometimes they're called isolation joints.

In locating expansion joints, the designer must recognize the fact that every parking structure has a set of site conditions, a shape and size that are unique. If the structure is permitted to move at points of natural change and reasonable intervals along its length, the design is adequate.

Because expansion joints are constantly subjected to wide movement, they should be fitted with a prefabricated assembly that is regularly produced for this special purpose. Many manufacturers who produce several product types are available.

b) *The Control Joint*

It is needed prior to the beginning of the concrete slab shrinkage, when the slab assumes its deflected shape under load, or moves over the particular structural frame that supports it.

Control joints should be located at places where cracking strains can build up. Only a shallow slot in a slab surface is usually needed to direct concrete shrinkage to manageable places. The cuts must be made prior to shrinkage in the concrete.

c) *The Construction Joint*

It is needed at the completion of a given day's concrete slab pour; or provides a desirable post-tensioning interval. This type of joint is where a great number of leaks typically occur and is often not given much attention by the designers.

2. *Joint Sealants*

The basic ingredients of most modern sealants are urethanes. Only high-quality products capable of withstanding traffic abuse should be considered. Every component, including the backing rod should have a long successful history in similar joints, be non-absorbent of moisture and should not be attacked by de-icing chemicals or ultra-violet rays.

The most important requisite for the particular products that are to be used is their preliminary selection prior to pouring the concrete so that the right-shape groove for sealing materials can be left in the concrete. Unfortunately, the sealant often fails because it was placed in a joint that had the wrong shape. The important bond-breaker at the joint's bottom should not be overlooked. The sealant manufacturer is a proper source for advice in joint design, and to supply the appropriate requirement data for contact drawings.

4.4. Drainage System

Concrete is not a waterproof or watertight material. While the concrete permeability can be reduced by quality control and admixtures, it cannot be eliminated. When water is allowed to lie on concrete surfaces it will eventually find minute, virtually invisible cracks that exist in all concrete.

As part of their drainage systems, parking deck slabs should have a minimum specified slope all over, including relatively flat, transition areas. It is essential that all levels have a well-designed inlet and piping plan for carrying off the water from a low point.

Good drainage reduces concentrations of de-icing chemicals that can attack reinforcing steel within the slab. Good drainage will increase the useful life of a parking structure.

4.5. Surface Sealers

Sealers are liquids that are applied to the concrete surface for the purpose of either curing or resisting water penetration. Many of the available sealers are suitable for parking structures, but a number are not. None of them should be considered capable of producing complete permanent waterproofing. They cannot act as a substitute for properly constructed systems of both jointing and drainage.

Since surface sealers are relatively clear and hardly noticeable liquids, their maintenance is often overlooked. To remain effective, sealers require periodic re-application every few years, in heavy traffic areas.

1. *Types of Sealers*

Two groups of synthetic sealers, particularly suitable for parking structure decks, are classified by the amount of penetration and surface film they can provide. As long as they are chemically compatible, both may be used in the same building and tailored to exposure.

a) Deep Penetration, No Appreciable Film

These chemicals react with the concrete's cementitious elements, and thereby cause the repelling of water. Compatibility with concrete aggregates should be verified. Silanes and siloxanes are the basic chemicals of these penetrants; while they are more expensive, they provide good performance.

A newer class of water based penetrating sealers is now available containing fluorocarbons. These provide oil and grease resistance in addition to water resistance (Adams, 2001).

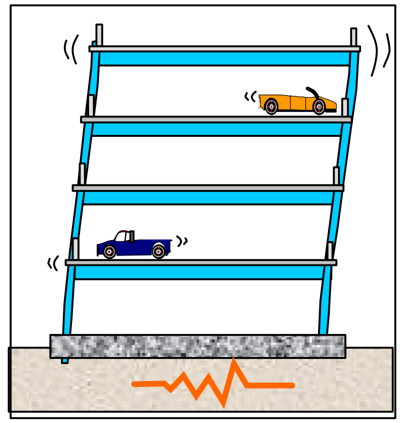
b) Slight Penetration; Continuous, Visible Surface Film

This group as compared to the Deep Penetration, No Appreciable Film, is more extensively harmed by traffic wear and natural deterioration. While it is less expensive, its life is shorter. In these coatings, the basic chemicals are urethanes, epoxies, acrylics, and other polymer resin blends.

These sealers deposit a durable clear or pigmented film on the surface. It acts as a physical barrier to resist water, oils and even acid. The film may change the surface appearance and will have to be resealed occasionally due to traffic abrasion. This type of sealer may be acrylic, urethane, epoxy or a blend of two or more resins (Adams, 2001).

Sealer manufacturer's use-instructions should be carefully followed for both preparation and application. Surface preparation is very important; even a new concrete slab must be clean and sound prior to application of a sealer. A test patch using the selected sealer should be done to determine suitability *before* beginning a large project (Adams, 2001)

5. NOTES ON SEISMIC DESIGN



5.1. Seismic Performance Criteria for Parking Structures

Current seismic design of typical residential or office buildings strives to satisfy the following performance criteria:

1. The building should survive small and moderate earthquakes that occur frequently with minimal damage that can easily be repaired. In addition, in recent years, in many cases, seismic design is done such that the building remains functional and occupied after a small or moderate earthquake, and;

2. The building should survive major earthquake without collapse, loss of life or major injuries.

Application of the above performance criteria is quite justified for modern residential and office buildings. However, there are a number of differences between a parking structure and a typical residential or office buildings that may warrant a slightly different seismic performance criteria for parking structures. The main differences between a parking structure and a typical residential or office building are:

- Unlike residential and office buildings where considerable non-structural elements such as partitions, walls, claddings and windows exist, in a parking structure, usually there are very limited amount of non-structural elements and the bulk of the building is primarily a bare structure.

- Unlike residential and office buildings, mechanical equipment and lifelines in a parking structure are very limited.

- Unlike residential and office buildings where the structure and particularly connections are usually covered by fireproofing and non-structural elements, in parking structures, almost all structure is exposed and any damage can easily be detected and repaired.

Considering above differences, it appears that there is a need for a different drift limitations for parking structures than the limitations currently prescribed in building seismic design codes International Building Code (ICC, 2000), Uniform Building Code (ICBO, 1997), and SEAONC Blue Book (SEAOC, 1999). It appears that the drift limitations in current codes have been established to prevent excessive damage to non-structural elements and mechanical systems of a typical residential or office buildings. Of course, excessive drifts can result in increased P-delta effects and considerable reduction in load carrying capacity of columns. However, such excessive drifts, in the order of a few percentage of floor height are well beyond the current code drift limitations. It seems that parking structures are facilities that are closer to a bridge than a residential or office building. In both parking structures and bridges, cars are the main load and main occupier and in both cases, the facility is almost a bare structure with minimal non-structural and mechanical components. Therefore, it seems reasonable that a more realistic limit for drift limitations of parking structures be established. It seems that such a drift limit should be related to structural performance and not preventing damage to non-structural elements.

Based on above discussion, for open parking structures, where there are very few non-structural and mechanical elements, the following seismic performance criteria are suggested. The main difference between this proposed criteria for parking structures and the criteria presented for buildings at the beginning of this section is in the first criterion regarding serviceability and damageability during small and moderate earthquakes. The proposed criteria is:

1. The parking structure should survive small and moderate earthquakes that occur frequently with minimal damage *to its structure* that can easily be repaired. In addition, the structure needs to return to its plumb position, and;

2. The parking structure should survive major earthquake without collapse, loss of life or major injuries.

5.2. Gravity and Seismic Loads for Parking Structures

The information in this section is based on current International Building Code (ICC, 2000). For actual loading of a parking structure for design purposes, the reader needs to refer to the actual governing code.

The dead load of a parking structure is established the same way as any other structure and current codes do not have any provisions specific to parking structures. However, since in a parking structure, the bulk of dead load is due to the weight of structural elements and the dimensions of these elements usually involve less uncertainty than the non-structural elements, it appears that a dead load combination factor of lower than 1.2 (the current code value) may be justified for parking structure. Until further research on this item is conducted, the load factor of 1.2 as specified by current codes should be used.

The live load specified by current codes for parking structures (i.e. parking structures with passenger cars only) is 50 pounds per square feet in IBC-2000 (ICC, 2000) and UBC (1997). The

IBC-2000 also specifies that: "Floors in garages or portions of building used for the storage of motor vehicles shall be designed for the uniformly distributed loads of Table 1607.1 (which is 50 psf for parking structures) or the following concentrated load: (1) for passenger cars accommodating not more than nine passengers, 2,000 pounds acting on an area of 20 square inches; (2) mechanical parking structures without slab or deck, passenger cars only, 1,500 pounds per wheel.

Section 1607.9.1.2 of the IBC-2000 specifies live load reduction for passenger car garages. It states*: " The live loads shall not be reduced in passenger car garages except the live loads for members supporting two or more floors are permitted to be reduced by a maximum of 20 percent, but the live load shall not be less than L as calculated in Section 1607.9.1 (ICC, 2000a."* For more information, the reader is referred to the actual code (ICC, 2000).

In seismic design and in establishing total dead load of the building, W, to be used to calculate base shear, according to IBC-2000, (ICC, 2000) floor live load in public garages and open parking structures need not be included.

5.3. Lateral Load Resisting Systems for Parking

Common lateral load resisting systems used in steel structures today are:

a. Concentrically braced frames
b. Eccentrically braced frames
c. Moment frames (Fully Restrained, FR)
d. Semi-rigid frames (Partially Restrained, PR)
e. Steel shear walls
f. Dual systems combining moment frames with either braced frames or shear walls
g. Composite (steel and reinforced concrete) systems

All of the above structural systems can be used in parking structures with some being more economical than others are park. In general, in order to achieve better economy in steel parking structures the following basic principles suggested 30 years ago in a US Steel publication seems still valid:

"

- *Employ shop labor and prefabrication as much a possible.*
- *Employ standard AISC connections when possible.*
- *Avoid full penetration welding especially in the field.*
- *Use braced frames, as opposed to achieving lateral stability through moment connections*

(Excerpt from Ref. (USS, 1971)) "

In the following sections, some advantages and disadvantages of using each structural system in a parking structure are discussed.

5.3.a. Concentrically braced frames

The concentrically braced steel frames are one of the most economical, if not the most economical, lateral load resisting systems. In most parking structures, it is possible to use this system in at least one direction. The X-braces might be more economical than the V-brace or Chevron braces that sometimes are used in buildings to accommodate door and window openings. The beam-to-column connections in this system can be the more common shear tabs (Astaneh-Asl et al, 1989) or any other standard AISC shear connections such as seat angles, stiffened seat or web angles. The bracing members can be single angle, double angles, single channels, double channels, tubes, pipes or wide flanges. The end connections of bracing members are usually gusset plates.

Current design codes (AISC, 1997), include information on two types of eccentrically braced frames: (a) Special Eccentrically Braced Frames and (b) Ordinary Eccentrically Braced Frames. More design-oriented information on concentrically braced frames and their connections can be found in (LA-AISC-PMC and Flynn, 2000) and (Astaneh-Asl, 1998).

5.3.b. Eccentrically braced frames

Eccentrically braced frames can also be used in steel parking structures. However, compared to concentrically braced frames, eccentrically braced frames may not be as economical for this application.

5.3.c. Moment frames

Steel moment frames, especially frames with field full penetration welds, can be quite costly compared to concentrically braced frames. In many applications, because of interference with the ramps or driving lanes, braced frames cannot be used. In these cases, better economy of design can be achieved if at early stages of design, the fabricator is also involved in deciding the type and details of the moment connections. One of the best sources of information on seismic design of steel moment frames is the SAC steel Joint Venture publication FEMA-350 and four other reports in the series FEMA 351 through FEMA 354 (FEMA, 2000).

In addition to moment connections discussed in FEMA documents (FEMA, 2000), Collin and Putkey (1999) have proposed a welded connection that minimizes residual stresses. Details of this connection are discussed in the Steel TIPS report (Collin and Putkey, 1999). Studies of failures of field-welded connections during Northridge earthquake have indicated that relatively large residual stresses in full-penetration field welds may have been one of the parameters contributing to fracture of welds. According to Putkey (2001), "*Improper root openings were a probable cause of weld failures in the Northridge earthquake.*" The connection proposed by Collin and Putkey (1999) appears to be a clever solution to avoid residual stresses. Collin and

Putkey state that: " *Our suggested connection avoids direct beam flange to column flange welds and restrained cover plate to column flange welds. It eliminates medium or high residual stress that occurs when welding these joints to a column flange because connection restraint or member restraint is not present…*" (Collin and Putkey, 1999). Using the connection proposed by Collin and Putkey one culprit, the residual, stresses can be effectively kept out.

Shop-welded field-bolted column-tree moment frames can also be very efficient system for parking structures. In a column-tree system, a short length of girder is welded to the column in the shop. During erection of the frame, after columns are erected, the girders are placed between the column short girders and are spliced to them, Figure 5.1. By placing the splice point near the point of inflection of beam under gravity load, the girder splice can be designed to carry shear due to gravity combined with shear and moment due to seismic load. As a result, the splice will be reasonably small. In fact, one can take advantage of this splice and design moment capacity of the splice less than the capacity of the girder and the beam-to-column welded connection. By doing so one can make the splice to be the weakest link in the bending moment diagram with the highest demand to capacity ratio as shown in Figure 5.2 forcing plastic hinge in the girder to form in the splice. The plastic hinge formed in the splice will act as a fuse and protect the welded connection at the face of column from fracture as well as the girder flanges from local buckling. More information on seismic behavior and design of column-tree moment frames can be found in Astaneh-Asl (1997). In designing steel moment frames, bolted moment connections can also be very economical.

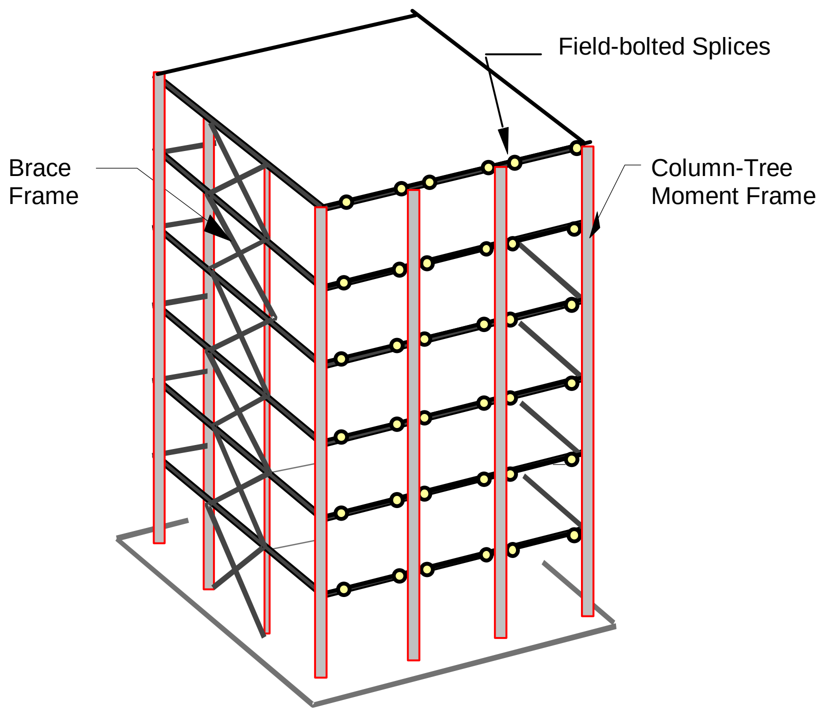


Figure 5.1. Column-Tree Moment Resisting Frame

Since the 1994 Northridge earthquake and the increased cost of making full penetration filed-welded moment connections more ductile, the bolted moment connections such as top &

bottom bolted plate connections have become quite economical and have been used in many structures in various seismic regions of the West Coast. More information on seismic design of bolted moment frames can be found in (Astaneh-Asl, 1995), (Astaneh-Asl, 1998) and FEMA 350 Report (FEMA, 2000). The fact that in a parking structure most connections are exposed makes bolted connections more desirable since in the aftermath of a major earthquake all one has to do is inspect the connection bolts and if any bolt was found sheared off or loosened simply replace and/or tighten them.

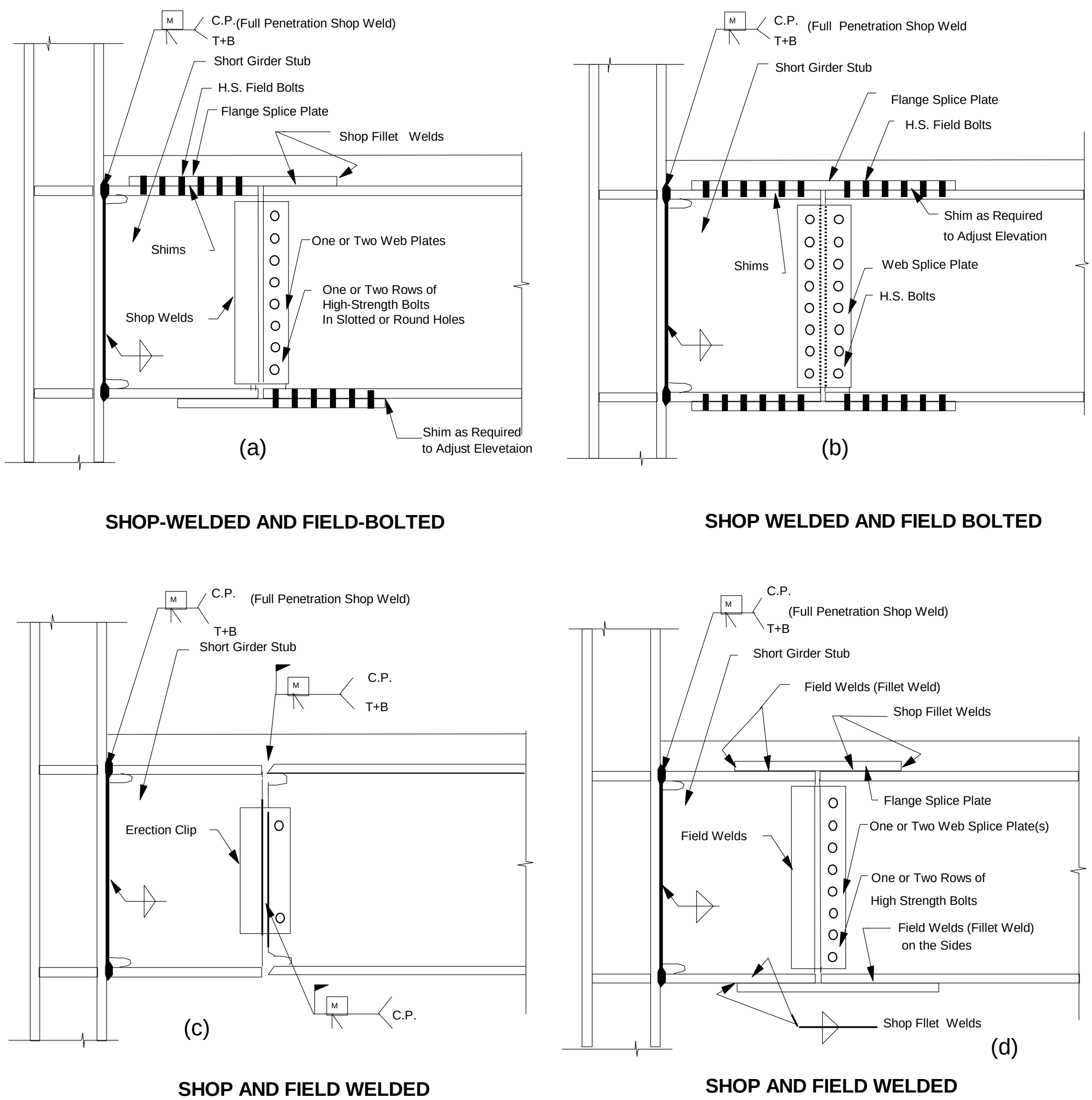


Figure 5.2. Suggested Details for Column-Tree Moment Frame (Astaneh-Asl, 1997)

5.3.d. Semi-rigid (Partially Restrained) Frames

Numerous analytical studies, laboratory tests and observations in the aftermath of actual earthquakes, all have indicated that semi-rigid (PR) steel frames have the best balance of stiffness, strength, damping and ductility to resist seismic forces with economy and efficiency. The reader unfamiliar with seismic behavior and design of semi-rigid frames is referred to references (Nader and Astaneh-Asl, 1989), (Nader and Astaneh-Asl, 1992) and (Astaneh-Asl, 1994).

The benefits of using semi-rigid (PR) steel frames to carry gravity and wind loads have been recognized during the last 20 years and a number of semi-rigid steel structures have been designed and constructed in U.S. However, even though steel semi-rigid frames are perhaps one of the most suitable structural systems for seismic areas, they are one of the least utilized systems to resist seismic loads. The main reason for this lack of usage may be lack of explicit seismic code provisions for semi-rigid steel frames in current codes. Particularly, many structural engineers are concerned about large drifts that in their opinion a semi-rigid frame might develop.

Perhaps this feeling about large drift to be developed in semi-rigid frames has its roots in long-practiced “equivalent static load” given in current codes. In this method, seismic forces (which are actually dynamic inertia forces) are applied to the structure at floor levels as static forces. Then the structure is analyzed and member forces and story drifts are established. Following this method, if one uses semi-rigid frame in place of similar but rigid frame, the drift of semi-rigid frame would be larger. However, during an earthquake, the inertia forces developed in a structure are not static forces but they are dynamic forces and their magnitude depends on stiffness, damping, ductility, energy dissipation and dynamic properties of the structure and the ground motion shaking it. As a result, as shown by the research and shaking table tests conducted by Nader and Astaneh-Asl (1992) the drift and seismic forces developed in a semi-rigid frame can be in fact *less* than a similar but rigid frame. In the following, a brief summary of behavior and seismic design of semi-rigid frames is provided.

It appears that for low- and mid-rise structures and particularly for parking structures where there are very few non-structural brittle elements, semi-rigid steel frames can be the best and most economical lateral load-resisting system.

Steel rigid as well as semi-rigid moment frames resist seismic effects primarily by bending and forming plastic hinges within the moment connection area. The main difference between a rigid and semi-rigid steel moment frames is in the bending strength and rotational stiffness of the beam-to-column connections relative to the connected beams. In rigid frames, the connections are designed to be stronger and stiffer than the beam and are expected to remain essentially elastic during earthquakes. In semi-rigid frames, the connections are intentionally designed to have less bending capacity and stiffness than the connected beams so that the bulk of yielding and rotational ductility is in the connection elements and not in the girder.

Almost all semi-rigid connections used today are shop-welded field bolted or entirely field bolted. Rigid moment connections typically show bi-linear moment-rotation response with two distinct regimes of behavior: (1) the initial elastic behavior and (2) the post-yielding non-linear behavior. In steel semi-rigid connections, the moment-rotation behavior in general has four distinct regions: (1) the initial elastic region, (2) the first stage of softening due to yielding or friction slippage of the connection elements, (3) the secondary stiffening mostly due to kinematic hardening, and (4) the final yielding. In rigid connections with a given moment capacity, it is very difficult to control the initial rigidity which is generally very high. However, in today's common semi-rigid connections, all parameters of behavior such as initial stiffness, secondary stiffness, initial yield or slip moment, and final moment capacity can be controlled by choosing appropriate connection geometry and material properties (Shen and Astaneh-Asl, 1993; Nader and Astaneh-Asl, 1989 and 1992). Other studies, some of which are listed in the references, have shown similar behavior.

A comparison of the seismic behavior of rigid and semi-rigid steel moment frames reveals that the seismic forces generated in semi-rigid frames are generally less or on the same order as forces in comparable rigid frames. The lateral displacements of semi-rigid frames are usually slightly more than rigid frames. The decrease of forces and some increases in displacement in semi-rigid frames is attributed to elongation of period, increase in damping, decrease of stiffness at early stages of behavior, and the 'isolation effects' due to gap opening and closing in semi-rigid frames. If a semi-rigid steel structure has connections with sufficient ductility, the studies done so far, indicate that the behavior of bolted semi-rigid steel frames is superior to the behavior of welded rigid frames.

Currently most seismic design codes permit the use of semi-rigid steel building frames. However, the codes have very limited guidelines and provisions on how these structures should actually be designed. In the Uniform Building Code (ICBO, 1997), the AISC seismic Provisions (AISC, 1997) and the International Building Code (ICC, 2000) semi-rigid steel frames are categorized as "Ordinary Moment Frames" with a response modification factor of R equal to four. However, in the current codes, the composite partially restrained moment frames are placed in a separate category and are assigned an R factor of 6.0 which makes composite PR (semi-rigid) frames very competitive economically with other systems in seismic zones 1,2 and 3 and most likely competitive for low rise parking structures in seismic zone 4 as well.

5.3.e. Steel Shear Walls

Steel shear walls are being used more and more in tall buildings. Although current US seismic codes do not have specific provisions for steel shear walls, there is considerable information on seismic behavior of steel shear wall buildings and their seismic design that one can use and design safe and economical steel shear walls. A recent publication by second author (Astaneh-Asl, 2001) summarizes the available information on behavior of steel shear walls during actual earthquakes and in the laboratories, discusses code provisions for steel plate shear walls, provides information on how to design these systems and present suggested steel shear wall systems and details. It appears that steel plate shear walls, compared to braced frames, are more economical when used in high-rise buildings. Therefore, for low-rise parking structures, braced frames are preferred. In addition, unless shear walls are used within the perimeter frame or around the elevator shaft, they may result in obstruction of open view that is a desirable factor in parking structures.

5.3.f. Dual systems combining moment frames with either braced frames or shear walls

For low and mid-rise parking structures, it seems that there may be no need to use dual system, which compared to braced frame systems such as concentric braced frames may not be as economical.

5.3.g. Composite (steel and reinforced concrete) systems

Composite systems can be very economical systems in seismic areas for all structures particularly parking structures. By using composite columns and beams, one can economically optimize the cost and save on painting and fireproofing (for closed parking) costs. Current seismic codes and specifications have specific provisions on seismic design of composite structures (nternational Building Code (ICC, 2000) and AISC Seismic Provisions (AISC, 1997).)

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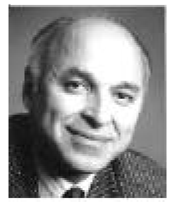

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