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Application of Light-Gage Cold-Formed Members to Modular Systems of School Construction in the United States

Application d'éléments de dalle orthotrope formés à froid à des systèmes modulaires de construction d'écoles aux Etats-Unis

Anwendung von kaltverformten Leichtbauelementen im Modularverfahren in Schulhäusern der Vereinigten Staaten

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Introduction

The nature of the building industry in the past has tended to isolate the development of building elements. The economic and technical requirements of one such element would lead to its development without full consideration being given to its integration into the total building system. There is an increasing interest in the United States in programs to reverse this trend.

One such program has been a California group formed in 1961 known as the School Construction Systems Development project (SCSD) of Palo Alto, California. This project was a joint activity of the School Planning Laboratory of the Stanford University School of Education and the Department of Architecture at the University of California at Berkeley. This activity functioned under a grant from Educational Facilities Laboratories, Inc., a non-profit corporation established by the Ford Foundation. The project architect was Ezra D. Ehrenkrantz.

A set of functional performance specifications was developed for several major components of the total building system. These specifications were used by a group of 13 California school districts for bidding purposes for establishing a modular system to be used on 22 school projects. The stated objective of the specifications was to develop "an integrated system of standard school building components which will

(1) offer architects desired design flexibility in meeting the changing program needs of individual schools,

(2) reduce the cost of school construction and give better value for the school building dollar in terms of function, environment, first cost and maintenance, and

(3) reduce the time needed to build a school."

It was felt by SCSD that often the educational methods were determined by building limitations. The specifications were formed around the premise that the building should fit the educational requirements, both present and future.

The component categories for which specifications were developed are Structure; Interior Partitions; Heating, Ventilating and Cooling; Lighting-Ceiling; Furniture; and Lockers. Each component category was required to be fully compatible and integrated with the others. All categories were to be designed to be compatible with a 5 foot by 5 foot planning module.

The Structure Category included the entire structural system except the exterior walls, the vertical shear resisting elements, the foundation, the slab on grade, and stairs. Some of the dimensional criteria were as follows:

(1) In academic areas, the maximum unobstructed area was to be approximately 7,200 square feet.
(2) The maximum depth of floor and roof construction from the top of the deck to the bottom of the ceiling was not to exceed 36 inches and would be the same depth throughout. The depth of the gymnasium roof construction would not exceed 60 inches.
(3) Changes of elevation of the slab on grade would be in increments of 2 feet.
(4) Roof spanning members were to be in 5 foot increments between 30 feet and 75 feet. Gymnasium roofs were to be 90 feet and 110 feet. Floor spanning members for use in two-story buildings were to be 30, 40, and 45 feet.
(5) Primary elements were to be available in 5 foot increments between 10 feet and 30 feet.
(6) Ceiling heights were to be in 2 foot increments between 10 feet and 18 feet. Gymnasiums were to have 25 feet from the floor to the bottom of the roof structure.
(7) Cantilevers of 5 or 10 foot spans were to be provided on roof spans.

The structural system was to be designed to the Code requirements of the Schoolhouse Section of the Office of Architecture and Construction of the State of California, which include provisions for resistance to earthquake forces. Horizontal diaphragms were to be part of the Structure Category. However, as previously mentioned, vertical shear walls or bracing were to be outside the Category. The light gage steel code requirements of this agency basically follow the provisions of the 1962 Edition of "Specification for the Design of Light Gage Cold Formed Steel Structural Members" of the American Iron and Steel Institute.

The SCSD system was bid and has now been completed with a total of 1,400,000 square feet of school buildings being built in California.

Four systems have been developed which are based on the SCSD Specifications and use elements composed of light gage cold formed steel. These systems are now described in some detail.

Inland Steel Products Company (Milwaukee, Wisconsin)

The systems developed by this company are called the Inland Modular Systems. They consist of an integrated structural system and compatible ceiling-lighting system. Both were specifically designed for and used in the SCSD program. The structural system consists of three main components: The truss-deck, the primary truss, and the column.

The truss-deck unit is a simple span truss which used a 1-1/2 inch deep light gage, cold rolled steel deck as a roof covering, as the top compression chord of the truss, and as a horizontal diaphragm. The deck flutes run parallel to the truss-deck units spaced at 5 feet on center. Light gage, cold-formed, hat-shaped purlins running perpendicular to the truss-deck units support the deck also at 5 feet on center. Vertical load supported by the deck is transferred by the purlins to the top chord panel points of the trusses. To complete the top chord connection, horizontal light gage shear plates welded to the under side of the deck distribute horizontal forces into the deck from the truss-deck web members. Thus the deck flutes act as beam-columns.

The web members are cold-formed steel tubes, 1-1/2 inches square in various thicknesses. They are welded into a U-shaped bottom chord and are cold rolled, light gage steel having a yield strength of 50,000 pounds per square inch.

Truss-deck units were designed for roof spans from 10 to 75 feet in 5 foot increments. These trusses are all 33 inches deep out-to-out. For gymnasium spans, 90, 100 and 110 foot truss-deck units having a 57 inch deep truss are used. These trusses plus most of the roof spans can support either a 5 or 10 foot cantilever.

Truss-deck units for floors were designed in spans from 10 to 45 feet.

These are similar to the roof units except that a 3 inch thick lightweight concrete slab is added. In order to achieve a composite action and transfer horizontal shear forces into the slab, Inland's Hi-bond deck was used along with a specially formed shear connector welded at the truss panel points. Inland Hi-bond deck is similar to the roof deck but with a raised pattern of slanted ridges in the vertical elements of the deck flute.

All truss-deck units are shop assembled with the deck and purlin hinged to the truss to permit folding for ease of shipment. As the deck is unfolded during erection in the field, a predetermined camber is automatically obtained. This is accomplished by horizontal camber screws pre-set in the shop which bear against the purlins.

The truss-deck units are designed for basic roof live loads of 20, 25, 30 and 40 pounds per square foot and basic floor live loads of 70 and 100 pounds per foot. In addition to supporting the normal roof and ceiling loads, all roof truss-decks have been designed to carry the roof top heating, ventilating and air conditioning (HVAC) units at any location of the roof.

Transverse distribution bracing and diagonal bracing elements were designed to serve as bridging for the truss-deck units, to collect and distribute horizontal forces and to transfer horizontal forces between the top and bottom chord levels.

The primary truss supports the truss-deck units. It is a Warren type truss with a 33 inch constant depth out-to-out. It was designed in span lengths from 10 to 30 feet in 5 foot intervals. Five and ten foot cantilevers are also available for the longer trusses. Rectangular tubular members of high strength steel are used for the top chord and web members. The bottom chord is composed of either cold rolled double channels or bars, also of high strength steel.

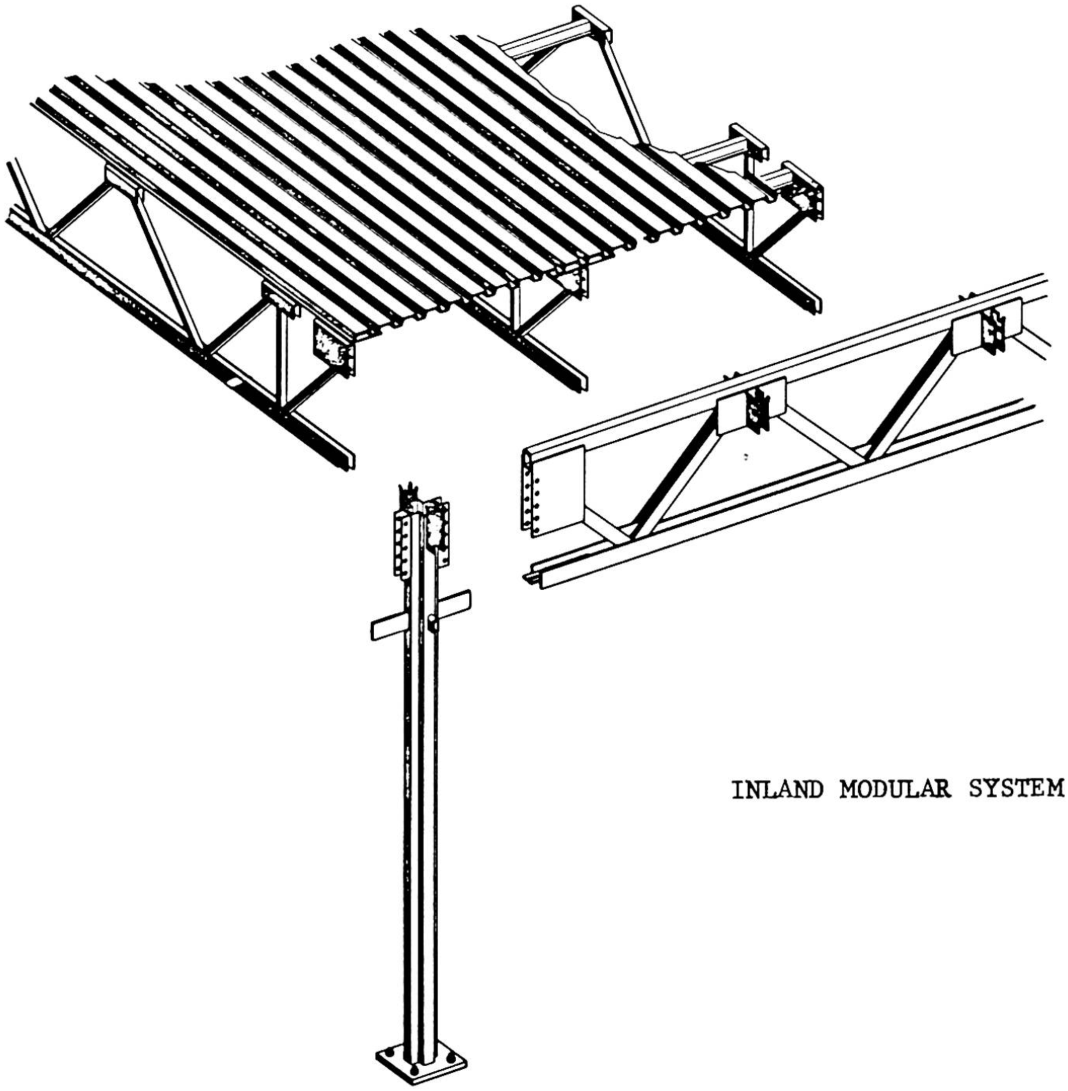
To facilitate the various combinations of truss-deck units for end and interior spans, primary trusses have been designed for a range of load capacities. Each span length is available in 9 to 10 different load classes.

Columns are hollow cruciform shaped in cross-section with a constant out-to-out dimension in each direction of 7 inches. The load-carrying capacity is varied by various wall thicknesses and by the use of high strength steels. Standard column lengths were designed in 1 foot increments to a nominal 30 feet. The cruciform shape with its indented corners has been designed for compatibility with interior partitions. It allows these partitions to intersect at columns without a corner obstruction. It also allows the standard Inland ceiling units to fit at the columns the same as they do at interior modules. One and one-half hour fire resistance rating for these columns is attained by the application of an intumescent coating at the outside and by filling the inside with concrete.

One of the principal advantages of this system, as well as all the systems described in this paper, is the speed of field erection. After columns have been placed, the primary beams are bolted to the column connectors with high strength bolts. The truss-deck units are then lifted into place between primary beams or columns. Steel pins engage in slotted end connectors. Decks are then unfolded into plate. The end connections are completed by the addition of more high strength bolts. The steel deck and purlin elements are then welded to the trusses. Fillet welds are applied between the shear plates and top gusset at each truss panel point.

Shear transfer units may be required in order to achieve lateral stability due to wind or seismic loads. Lower column connections connecting the lower chords of both the truss-deck and the primary truss offer some lateral restraint. However, since the columns are limited in their moment capacity and are primarily designed for vertical load, often additional bracing is required. This may be accomplished by fastening truss-decks or primary trusses to shear walls, by adding cross bracing between columns or by any other suitable means the engineer chooses.

After the structural system has been erected, the ceiling-lighting system may be installed. The Inland System offers metal coffers which fit into the 5 foot by 5 foot module and allow for either recessed or flush type lighting to be installed. Light gage, cold formed elements are also present in the ceiling system. The ceiling-lighting system, as well as the interior partition system, has been designed for the seismic loads required by SCSD.



INLAND MODULAR SYSTEM

The development of this system was done with thorough theoretical design and comprehensive tests. Structural tests were conducted to verify the adequacy of indeterminant welded connections, to check assumptions used to calculate deflections, and to confirm the adequacy of the criteria used in design of the entire system for sustaining the design loads. Three major tests and numerous smaller tests were conducted. An initial large scale test was performed in Los Angeles prior to the award of the SCSD contract. The purpose of the test was to demonstrate performance of the system under applied vertical, lateral, and combined loadings. The test specimen used consisted of 5 roof truss-deck units forming a 25 foot by 55 foot bay. The test demonstrated close conformance with predicted stresses, deflections, and determined diaphragm shear values.

A floor test was then performed using a 10 foot by 45 foot specimen. Loading was applied in three phases over a 6 month period. In addition to measuring deflections and the amount of rebound after initial and final loadings, creep during a 6 month duration was measured under static load. Test cylinders determined concrete strength over this same time period. Composite action between the steel deck and concrete slab was confirmed, as well as the adequacy of the special shear connector and the ability of the truss-deck units to sustain more than twice design loads.

A third major structural test was performed using a 20 foot by 70 foot roof truss-deck specimen. The major objectives were (1) to determine the performance of the purlins to both support the deck and provide bracing for this compression member, (2) to examine the stresses around framed openings in the deck, and (3) to measure stress distribution across the deck between trusses. Several of the purlins were bridged across before loading was applied in order to isolate the stresses due to staying the compression member from the direct vertical load stresses. Strain gages were applied at critical areas. Test results indicated (1) bracing action exhibited by the purlins was less than 1% of the deck compressive force, (2) the reinforcement used around large openings was more than adequate, and (3) the stress distribution in the deck was concentrated at the panel points at purlins and distributed between purlins confirming the theoretical analysis.

Fire tests were also performed under the auspices of the Underwriters Laboratory in Chicago, Illinois. Ceiling-lighting components, columns, roof and floor systems combined with the ceiling-lighting system were among those items tested. As a result, a 1-1/2-hour rating for the columns, and a 1-hour rating for the roof and ceiling assembly was obtained.

Butler Manufacturing Company (Kansas City, Missouri)

The system developed by this company is called the Space Grid System. It was developed for bidding the SCSD system. However, the floor elements are not now included as part of the system.

The horizontal spanning members of this system are simple span pyramidal shaped Space Trusses assembled adjacent to each other and bolted together. The Space Trusses maintain the basic 5 foot by 5 foot module. All members of the Space Truss are light gage cold-formed steel shapes. The lower chord of each Space Truss is composed of two approximately 5 foot on center shapes. When each is bolted to its mate of an adjacent unit, a 1 inch space is maintained for passage of air, electrical, and water services between the roof-ceiling envelope and the room space. A fluted transverse base member fastens each lower chord shape of the Space Truss element at 5 foot intervals. Ceiling and lighting panels are then supported by the lower chords and the transverse base members.

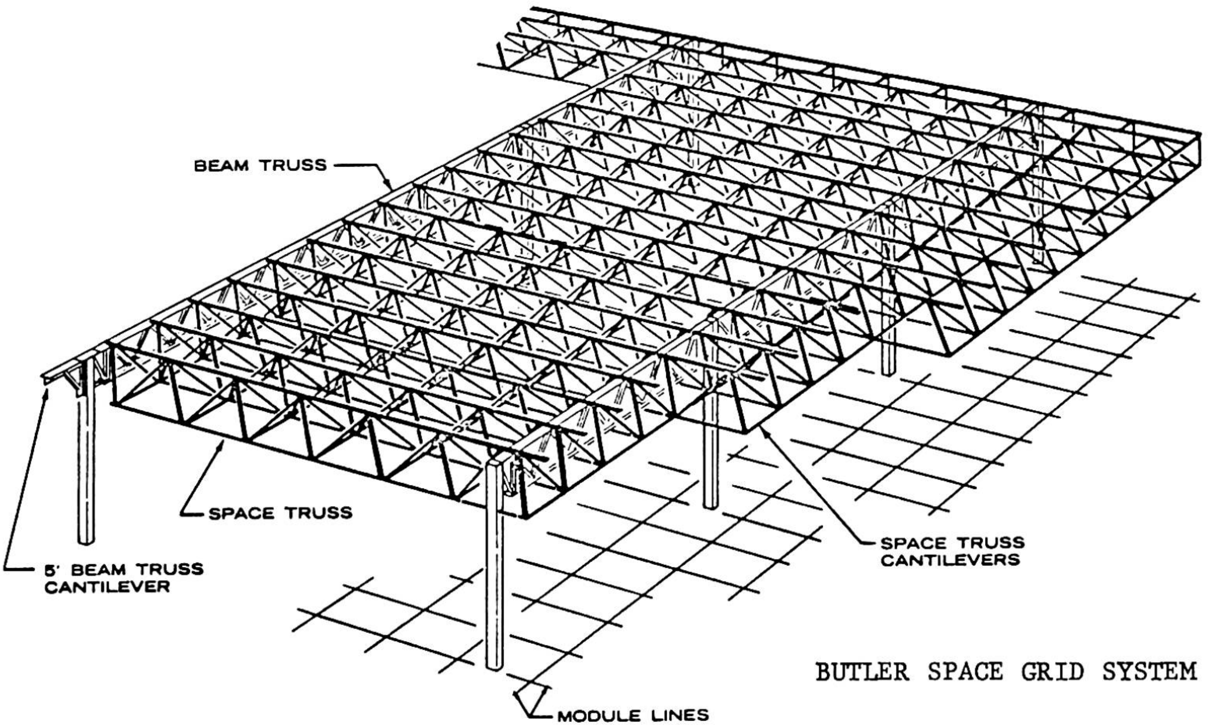
The upper chord is a fluted shape set midway between the two lower chords. Web members are bent plates welded and bolted to the upper and lower chords in the form of a pyramid. The Space Trusses are 35" deep out-to-out.

The Space Trusses are available in 5 foot increments from 20 foot spans to 40 foot spans. Cantilevers of 2-1/2, 5, 7-1/2, 10, and 12-1/2 feet are also used. The design of the Space Trusses and their supporting elements are based on three basic loading requirements as follows: (special load categories can be designed)

(1) 20 pounds per square foot live load or 15 pounds per square foot wind load with a maximum Space Truss span of 40 feet.
(2) 30 pounds per square foot live load plus 20 pounds per square foot wind load with a maximum Space Truss span of 30 feet.
(3) 40 pounds per square foot live load plus 20 pounds per square foot wind load with a maximum space truss span of 30 feet.

The Space Trusses are supported on tapered steel beams or Beam Trusses composed of welded structural tees and angles. The beams or Beam Trusses are available in 5 foot increments for spans between 30 feet and 75 feet at a depth of 31 inches out-to-out. For gymnasium spans, the beam or beam trusses are deeper than the standard envelope. Cantilevers are available in 5 and 10 foot spans. Mechanical passage is achieved through the Beam Truss or at the tapered ends of the beams. Specially reinforced holes through the beam web can also be used. One or two-hour ratings can be obtained using compatible fire-rated elements.

The beams or Beam Trusses are supported on 8-inch square tubes. Columns are of lengths to provide 9, 10, 11, 12, 14, and 16 foot ceiling heights. Other heights and changes of level are available within certain limitations.



BUTLER SPACE GRID SYSTEM

The roof covering is normally provided with an 1-1/2 inch deep light gage cold rolled steel deck which in combination with the Space Truss system acts as a diaphragm for resisting horizontal forces due to wind or earthquake.

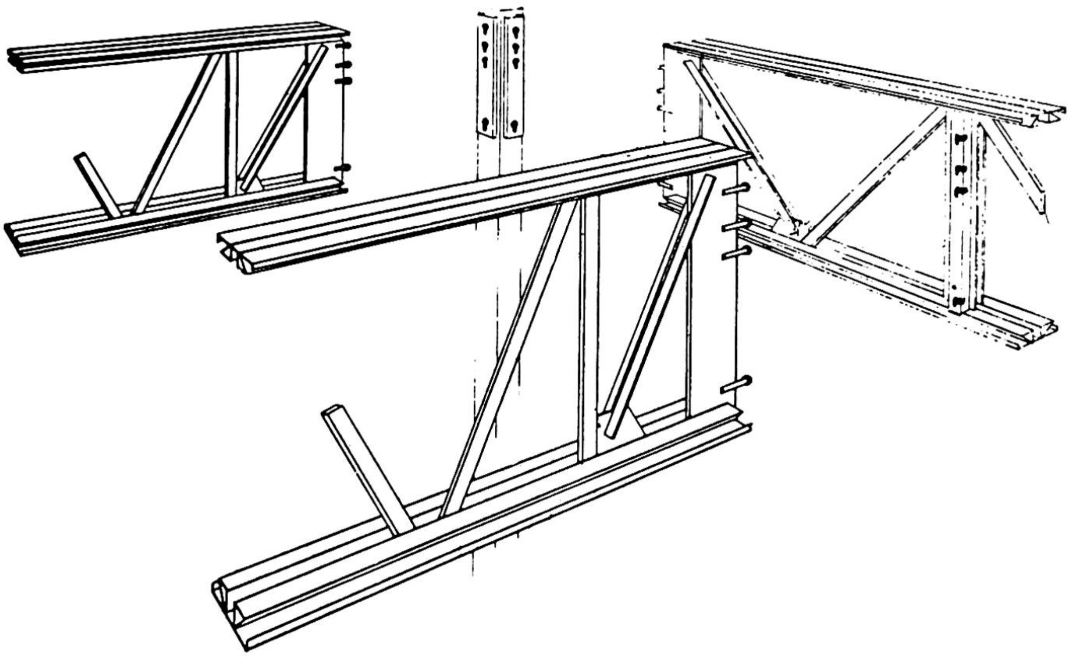
There are several fascia configurations offered in light gage steel. However, the Space Grid system is adaptable to many different fascias as may be required by the architect.

Macomber Incorporated (Canton, Ohio)

The system by this company is called the Macomber V-Lok Modular Component System (VLMC). It was developed subsequent to the bidding on the SCSD Specifications but the design principles of the system would permit it to be applied to the SCSD requirements. The columns, which would be located on the 5 foot by 5 foot planning module, can be either cold rolled or hot rolled tube sections or wide flange structural shapes. The standard column sizes are 5 inches by 5 inches, 6 inches by 6 inches, or 8 inches by 8 inches. Within these limits, the engineer can select the column required by his design from three cold-formed tube columns provided by Macomber, or any size listed in the "Manual of Steel Construction", Sixth Edition, of the American Institute of Steel Construction. Standard ceiling heights are 9 feet and 10 feet but may vary at the option of the architect or to meet partition disciplines.

The open web girders are supported by the columns and are connected to them with a special interlocking device called the V-Lok connection. The chords are cold rolled steel shapes. The webs are of tubular elements. The out-to-out depth of the girders is a constant 36 inches. Five and ten foot cantilevers are available for most girder back-up spans. The girder spans are in 5 foot increments up to a maximum of 45 feet. The girders are designed for 7 load classes, depending on the applied panel point loading.

The open web purlins are formed using cold rolled chords and tubular webs. The purlins are connected to girders and columns using a V-Lok connection similar to that used to support the girders. The out-to-out depth of the purlins is 36 inches for roof spans to 80 feet and floor spans to 50 feet. For long span roofs from 80 to 110 feet, the depth is 60 inches. Most purlins can support 5 or 10 foot cantilevers. Roof purlins are designed in 5 load classes of live load between 20 and 50 pounds per square foot. Floor purlins are designed in 6 load classes of live load between 40 and 100 pounds per square foot. Most purlins have also been designed to support the loads from mechanical unit components. All roof purlins are cambered for the maximum total deflection occurring with the member fully loaded. Floor purlins are cambered for dead load deflection.



MACOMBER V-LOK MODULAR COMPONENT SYSTEM

The roof covering is achieved using a 2 foot wide, 1-1/2-inch deep, cold rolled steel deck. The steel deck serves as a horizontal diaphragm to resist wind or earthquake forces.

Some sub-assembly elements have been provided, such as reinforcements around floor or roof openings, lower chord and lateral force bracing elements, fascia attachment elements, and wall lateral support elements.

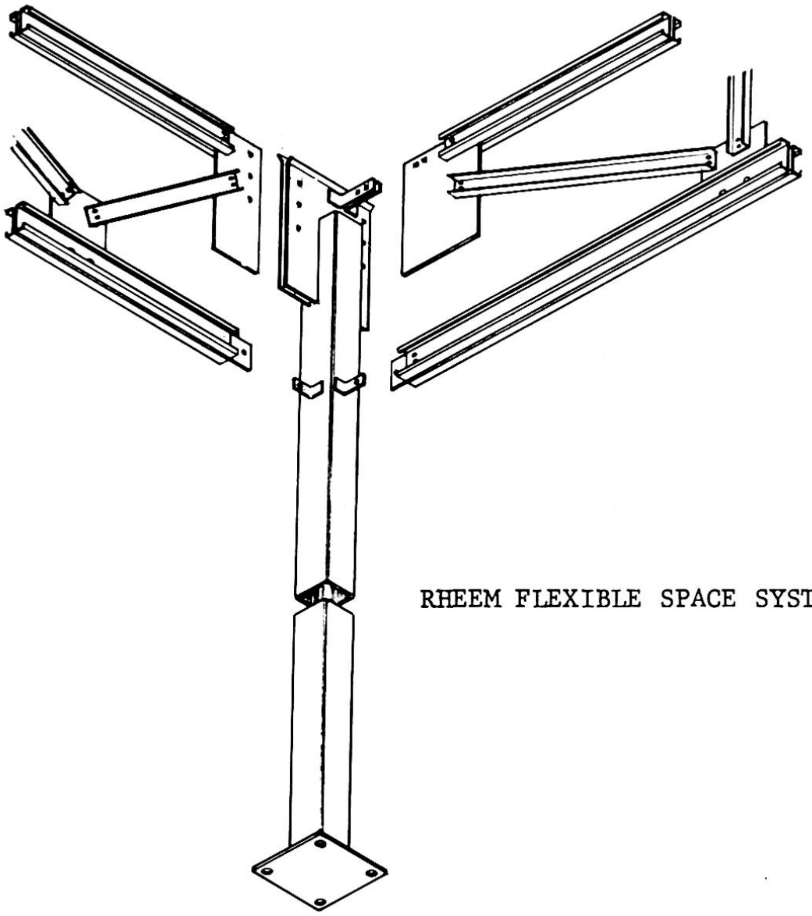
Combinations of compatible integrated components can be arranged to achieve a fire rating of up to 2 hours.

Rheem/Dudley Buildings (Paramount, California)

The system marketed by Rheem/Dudley Buildings is called Rheem Flexible Space Systems. It was developed by Compatible Design Systems of Santa Clara, California, subsequent to the awarding of the SCSD bid. The design principles of the system were based on the SCSD Specifications including compatibility with the various component categories. The main components of the structural system are framing trusses, primary trusses, columns, and roof deck.

The framing trusses are on the standard 5 foot module. The framing trusses of the Pratt type are available in roof spans at increments of 5 feet up to 75 feet with an out-to-out depth of 34 inches. Floor framing trusses vary in 5 foot increments to a span of 50 feet providing elements for 2 or 3 story buildings. For longer spans, the trusses are 64 inches out-to-out and are in 10 foot increments to 120 feet. Five and 10 foot cantilevers are also available for floor trusses and both depths of roof trusses. The chords of the trusses are two 4-inch channels ( ][ ) with varying gages for the various spans. Web members are two 2 and 3-1/2-inch channels ( ][ ) typically made with 14 gage steel. Webs and chords are bolted to 3/16-inch gusset plates. The top chords are sloped

1/4-inch per foot for drainage. At present, all truss joints are fastened using 1/2-inch high strength bolts.



RHEEM FLEXIBLE SPACE SYSTEM

The framing trusses are bolted to columns or primary trusses. The primary trusses of the Warren type are in 5 foot increments from 10 foot spans to 40 foot spans. Five and 10 foot cantilevers are also available. The chords are composed of 6-inch, light gage cold rolled channels (⊐⊏) or hot rolled channels (]⊏). The webs are composed of 3, 4, or 5 inch hot or cold rolled channels of varying depths and gages. Webs and chords at present are bolted to 3/8-inch gusset plates with 3/4 inch high strength bolts. Primary trusses were designed in 9 load classes to accomodate interior and exterior conditions with economy.

The primary trusses and framing trusses are high strength bolted to a connector plate mounted on 6-inch square tubular columns of varying wall thicknesses. Column lengths, which can vary in one-foot increments up to a maximum of 40 feet, are determined according to the nominal roof elevation at the column. Columns are designed as pin-ended members and are divided into five different load classes.

The floor and roof decks are 1-1/2-inch fluted steel decks spanning perpendicular to the framing trusses with gage determined by the vertical loading or by the horizontal loading with the deck acting as a horizontal diaphragm. The deck is fastened to the framing trusses at predetermined points by welding or mechanical fasteners as required. On floor decks a 2-1/2 inch poured-in-place lightweight concrete fill is used.

Horizontal distribution bracing and diagonal struts are used between framing trusses to act as bridging and to distribute horizontal forces to the diaphragm.

The ceiling is directly supported by framing and primary trusses. A fascia may be supported on perimeter trusses.

In excess of the SCSD requirements, a compatible cross-brace assembly is provided to act as a shear wall on the primary truss lines if it is required.

All roof systems are designed to support the associated dead loads including mechanical equipment and live loads of 16, 20, 25, 30, and 40 pounds per square foot. Floor system live loads are a basic 70 or 100 pounds per square foot. One-hour ratings on columns and roof system have been given by code authorities.

All elements of the structural system were designed using the standard design criteria. No special testing has been required.

SUMMARY

The SCSD approach to the school building construction has aroused a nationwide interest among manufacturers, architects, and engineers in the use of integrated systems for various types of building construction. The systems developed under these specifications have been used successfully not only for schools but also for many industrial and commercial buildings throughout the United States. It has not only resulted in a more functional utilization of materials, but has provided a means of creating more efficient structures at reduced cost. New programs patterned after the SCSD program are presently under development and are evidence of the success of the concept of the SCSD System's approach to building construction.

RÉSUMÉ

La méthode SCSD pour la construction d'écoles a soulevé de l'intérêt dans tous les Etats-Unis chez les fabricants, les architectes et les ingénieurs pour l'utilisation de systèmes intégrés pour différents types de construction. Les systèmes développés sous ces spécifications ont été employés avec succès non seulement pour des écoles mais aussi pour bien des constructions industrielles ou commerciales dans tous les Etats-Unis. Il en a résulté non seulement une exploitation plus fonctionnelle des matériaux, mais aussi un moyen de projeter des structures plus efficaces à des prix réduits. De nouveaux programmes sortis du programme SCSD sont actuellement en cours de développement et démontrent le succès du concept de l'SCSD.

ZUSAMMENFASSUNG

Das SCSD-Verfahren hat für den Schulhausbau ein weites nationales Interesse unter Herstellern, Architekten und Ingenieuren hervorgerufen, wenn es sich um integrierte Systeme verschiedener Bauweisen von Gebäuden handelt. Dieses unter den beschriebenen Vereinfachungen entwickelte System ist nicht nur bei Schulen, sondern auch für viele Industrie- und Geschäftsbauten überall in den Vereinigten Staaten angewandt worden. Dieses Verfahren ist nicht nur Ergebnis einer besseren funktionellen Materialanwendung, sondern folgte auch aus der Absicht wirtschaftlicher Tragwerke und verminderter Kosten. Neue aus dem SCSD-Programm hervorgegangene Verfahren stehen zurzeit in der Entwicklung und sind Beweis des Erfolgs obigen Systems.

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