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INNOVATIVE DESIGNS WITH COLD-FORMED MEMBERS AND SHEETS

by

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ABSTRACT

This paper discusses innovative approaches to designing and building with cold-formed members and sheets. Use of cold-formed steel from diaphragm action to primary structure for large span buildings is presented and illustrated with numerous examples. Examples include both present applications as well as potential technology for cutting construction costs. Approaches to implementing unique designs with cold-formed steel are discussed and recommendations for required research are included. The potential for cold-formed steel to develop efficient economical structures as well as exciting architectural solutions is illustrated.

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I. INTRODUCTION

In recent years, the use of cold-formed members and sheets has become popular in the construction industry. Initially, applications concentrated on lightweight secondary structural members. Today we see more and more use of cold-formed steel for primary structural members. The confidence in the use of the material is due to favorable experience with previous applications; progress in defining structural behavior and presenting of such in guidelines in the AISI codes; and the application of sophisticated methods of structural analysis previously used in Aerospace Industries for light-gage stressed-skin structures such as airplane wings and rocket cases.

In a time where energy crises and availability of resources are key buzz words, I believe the utilization of lightweight construction which minimizes material weights is most apropos and has great potential for continued growth. Designing with light-gage cold-formed members and sheets, with emphasis on the use of geometry for strength as opposed to bulk of material, meets this criteria and provides for economical construction. To date, much has been done towards this end. This paper
discusses some of the background which got us here, the structural technology involved, and structural designs by Lev Zetlin Associates, Inc. and its research affiliate, Environspace, which illustrate state of the art use of light-gage cold-formed members and sheets as well as potential applications. The approach to implementing new designs and suggested additional research are discussed.

II. BACKGROUND

Light-gage metal construction has consistently been capable of replacing heavier more costly types of construction. The major uses of light-gage steel today are for roof decks, floors and walls. One method, widely used throughout the construction industry, is combining light-gage metal decking with concrete to form economical composite slabs which eliminate costly formwork. The reliability of the use of the material as a stressed-skin diaphragm has been demonstrated consistently in buildings where either on walls and/or roofs the diaphragm action of the decking participates in transferring wind loads.

Research on the performance of metal decking and girts (or purlins) acting together as a system has resulted in even further efficiencies as opposed to looking at them as separate structural components. Manufacturers of metal buildings are capitalizing on these capabilities and characteristics of cold-formed steel to provide minimum weight and economical building construction.
The advantages of light-gage steel construction have been significant enough to cause its application in the construction industry to grow from an infant business in 1948 to a major industry by 1960, with continued growth till today. Much of this growth is attributable to the development of manufacturing techniques and methods of connections which meet the needs of the industry.

As mentioned, the major use of light-gage steel has been for roof, wall and floor systems. In recent years, we have seen more use of the material as the primary structure for large span lightweight roofs, the hyperbolic paraboloid shape being the favorite. Potential design applications presently being considered include inflated metal membranes and main beam and girder members. Recent and potential applications are discussed below.

III. STRUCTURAL DESIGNS

Light-gage sheets have a high shear strength to weight ratio and have proven their efficiency as a structural diaphragm. This has permitted metal deck systems to provide diaphragm action in both floors and roofs of buildings to assist in transferring lateral loads due to wind or seismic forces. In pre-engineered metal building construction for example, the roof decking is used as a shear diaphragm to transfer wind loads from the end wall through the roof to the side wall system, usually containing cross bracing in some of the bays. The following
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designs illustrates unique use of the diaphragm capabilities of light-gage steel as well as other innovative uses of both cold-form sheets and members.

**Long Span Roof Shear Diaphragm**

Figures 1 and 2 show an example of utilizing light-gage metal as a shear diaphragm on a long span roof. The roof decking is supported by transverse trusses between shallow arches spanning 365 feet between abutments. There is no cross bracing between the arches and the trusses, because the decking is utilized as a stressed-skin to transfer lateral wind loads from the end walls to the abutments. The elimination of bracing resulted in a clean looking roof from the underside meeting architectural requirements as well as reducing costs.

The sections of decking are intermittently welded to each other near the abutments where the highest in-place shear is experienced, and in the center of the span the decking is fastened with button punching. The efficient use of the roof diaphragm complements the lightweight steel arch rib trusses which have an unusually low rise to span ratio, approximately 1 to 10.

**Stressed-Skin Composite Trusses**

An extension of the above concept is shown in Figure 3 where the decking was also used as a composite component of the prime structural system. Figure 3 illustrates an industrialized stressed-skin truss system designed for metal building applications. The roof decking doubles as a top cord of the truss minimizing the overall
material usage. The truss members are cold-formed shapes and, when utilized compositely with the decking, result in a weight saving of approximately 25% compared to conventional joists and decking.

Figure 4 illustrates a similar example on a larger scale for a roof designed to cover a submarine fabricating facility at a shipyard. Here the decking is also used as a top cord of the truss, but acts compositely with conventional hot rolled shapes.

In both cases, weight saving is attributable to the dual use of the deck as both the roof surface as well as a prime structural component. A study showed that the savings were greater with the smaller spans, below 100 feet, as opposed to larger spans. In the smaller spans, the same decking that would have been used just to act as a roof cover can double as top cord members of the truss. In the larger spans, heavier special decking is required.

Stressed-Skin Structures which Eliminate Trusses

The preferred approach to utilizing light-gage metal for long span roofs is to develop a form which permits the elimination of the heavy steel trusses. This stressed-skin approach has also been used as a design for a shipbuilding facility as shown in Figure 5. Long span hyperbolic paraboloid modules are used to obtain a clear span of 400 feet. The roof is supported by a wall system also designed with the hyperbolic paraboloid modules. The wall and the roof act together as a frame, providing the main structural system as well as the wall and roof enclosures at the same time.
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This approach is based on the design utilized for the recently constructed American Airlines Hangars shown in Figures 6 and 7. Two hundred and thirty foot long cantilevered hyperbolic paraboloid modules span over four 747 aircraft from a central core of the building. The hypar skin completely eliminated heavy trusses, and resulted in a roof that was 40% lighter than the conventional structure.

The hypar deck is fabricated from readily available components; 18 gage hat sections spot welded to 13 gage flat sections. Each 26 inch element of deck was placed along the straight line generators of the hyperbolic paraboloid and welded together with 3 inch fusion welds spaced at 6 inches. The design was based on an ultimate load of 10,000 lbs. per linear foot of shear force within the membrane. Of significant importance is the curvature of the hypar which, along with the bending stiffness of the deck cross section, prevents the shell from buckling at high shear forces.

Prefabricated Shell Modules

Figures 8 and 9 show a unique utilization of prefabricated lightweight shell structures used to construct the new Place desJardins' Mall Roof in Montreal, Canada. The entire roof, spanning 180 feet in both directions, utilizes the same repetitive 30-foot square stressed-skin module. This results in the advantages of highly efficient shell geometry while maintaining repetitive operations of construction which minimize field labor.
Each prefabricated module has the geometric form of a hyperbolic paraboloid. It is fabricated with hot rolled straight steel edge members, between which strips of cold-formed prefabricated light-gage metal decking are placed along the hypars straight line generators, forming the shell. As with other hypars, the shell transfers loads to the edge members by developing a state of in-plane shear stresses. The high shear strength to weight ratio of the deck makes its marriage with the hypar geometry a natural one.

The decking forming the shell is composed of a flat 13 gage section with 6 inch high 18 gage stiffeners spot welded to it. The flat section is the main structural element of the shell within which the shear stresses are developed. The hat sections act as stiffeners to both prevent local buckling of the flat sheet, as well as to increase the shells bending rigidity. The combination of the shells bending rigidity and its curvature prevents overall modes of buckling from developing.

A finite element computer program was used to assist in analyzing the roof structure. Although the individual behavior of a single prefabricated module is quite predictable by classical methods of analysis for roof loading, special attention had to be given to the interaction analysis between the modules. The finite element program analyzes both the loads transferred between modules, as well as the behavior of an individual module due to unsymmetrical loading conditions caused by these interface loads.
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Both tension rings at various elevations of the roof, as well as the cables shown in Figure 9, permit the roof to be supported by only 4 main towers providing a clear uninterrupted space below the structure. This type of design utilizes innovative geometry, but permits construction with readily available prefabricated deck components, forming larger prefabricated shell modules. The advantages of mass production and industrialization are thereby capitalized upon to reduce construction cost, while maintaining a unique architectural design which results in an aesthetically pleasing shell structure.

Other applications of using light-gage steel for long span roofs are shown in Figures 10 and 11. Figure 10 is a domed stadium where a hypar skin structure is utilized for both the roof and the wall system. The roof enclosure shown in Figure 11 is a permanent inflated stainless steel membrane which spans more than 350 feet to provide cover for a dog-track in Florida.

Stressed-Skin Pre-Engineered Buildings

A variety of industrialized buildings can be developed with standardized stressed-skin modules to provide for large economical spans. (See Figure 12) Figures 13 and 14 show a pre-engineered metal build designed for clear spans up to 300 feet. It is composed of long slender stressed-skin hypar modules which have open triangular cross sections. This permits nesting of the modules to facilitate and cut the cost of shipping.
The direction of the slope of the ridge member on each of the roof modules is alternated when erected. For example, the first module at the end of the building would have its high peak on the right side of the building, and the second module would have its high peak on the left side of the building and so on towards the rear of the building. This permits each module to simply be placed between the wall units during construction. The continuity of shell action throughout the roof, however, permits this type of construction to provide a frame action when the roof is connected to the wall system, which also makes use of the stressed-skin technology.

One of the main advantages of the system is its adaptability to a pre-engineered industrialized building system. For a given loading condition, the module geometry permits the slope of the ridge member to be constant regardless of the building span. This is possible because the slope of the ridge member is analogous to the vertical shear distribution for the structure, which governs the height of the rise of the shell at the wall.

Therefore, for a given loading condition, only one industrialized rig need be set up to construct the pre-engineered modules. Each module built in that rig would have constant width and a constant slope, and only the length would change based on the building span under consideration.
The economy of this system, therefore, is due to a combination of the efficient structural geometry, the dual use of the skin for cover as well as primary structure, the minimum number of components used in field construction, and its adaptability to economical prefabrication processes. The example discussed above is one class of buildings. A similar approach with a more symmetrical geometry forming a three hinge arch type of structure is shown in Figure 15. This was the basis for the shipbuilding enclosure design previously shown in Figure 5.

Buckling Resistant Sheet

Many of the above designs are based on the phenomena that curvature in a light-gage sheet will provide a geometry with additional built-in rigidities as compared to a flat sheet. This results in buckling loads an order of magnitude above that of a flat sheet. In a similar manner, flat light-gage metal sheet elements can be utilized for primary structure when they act compositely with other structural elements which will provide the bending rigidity necessary to prevent buckling. Examples include using rigid plastic foams to stiffen the sheet, or new expanded plastic cores as shown in the model in Figure 16. Here a new expanded plastic core is used to stiffen a light-gage metal web on the cross section of a 24 inch deep deck section. The deck can be utilized for spans up to 60 feet when acting compositely with a concrete slab. These design considerations are based upon the following phenomena.
Light-gage metal has a very high material strength to weight ratio. Its use is limited by its buckling strength just as a high-strength steel slender column may not be able to support much load due to structural instability.

If one braces a slender column at its mid-point, the buckling load of the column would be significantly increased, specifically by a factor of 4. Interestingly enough, the brace required need only be strong enough to provide a resistive force perpendicular to the column of less than 2% of the buckling load of the column. In a similar manner, an expanded plastic core bonded to light-gage metal provides a continuous bracing to prevent buckling waves from forming in the sheet. This significantly increases the usable strength of the material.

Beam and deck elements are being developed for an airport terminal system for the Port of New York Authority where the webs utilize light-gage metal reinforced by a plastic core. (Figure 17). Figure 16 shows a typical cross section in a model built in cooperation with a Steel Deck Manufacturer and the manufacturer of the plastic core. In this application, the core is being used to prevent shear buckling of a web which would manifest itself in a mode shape showing ripples at a 45 degree angle.

The bending rigidity of the plastic core when bonded to the light-gage metal assists the metal in resisting the formation of the buck-
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Innovative design techniques involve using wave-like patterns, thereby increasing its buckling strength. Because of the high ratio of the stiffness of deeper core to that of the thin sheet, there is a significant change in the bending rigidity of the composite web. Thus, significant increases in buckling strength are possible. Analogous to the brace in the column, which need not be strong relative to the column, it is the presence of the rigidity of the plastic that is most important, not its strength. This allows much flexibility in the use of materials, allowing for economical construction.

Other examples are shown in the beam elements used in Figures 18 and 19. In Figure 18, rigid urethane foam is bonded to a spanning element for a roof system. The foam provides insulation as well as acts as a stiffener to prevent local buckling of the light-gage metal. The diagonal fluting in the flange permits it to act as a transverse spanning element between webs. This diagonal fluting, however, does not negate the transfer of direct longitudinal compressive forces parallel to the beam span. The top flange of the metal decking, therefore, also acts as a compressive flange for the beam element. In a similar component shown in Figure 19, a combination of curvature and rigid foam is used to prevent buckling of the stressed-skin.

The use of stressed-skin structures has become commonplace in the aerospace industry and recently in the construction industry.
The economic feasibility of utilizing light-gage metal structures in lieu of heavy steel construction has been shown for civil engineering structures in the use of decking systems for floors, roofs and walls. The potential of this technology, in my opinion, reaches further.

**Light-Gage Construction for Rapid Transit Structures**

At Lev Zetlin Associates, Inc. we have recently developed stressed-skin designs for use in the transportation industry. Modern lightweight vehicles are currently being designed and put into use for personal rapid transit systems. These vehicles weigh in the order of 4,000 lbs. to 30,000 lbs., each, relative to conventional rapid transit vehicles weighing in the order of 100,000 lbs. to 200,000 lbs. Heavier high speed vehicles are also being developed which used a system of levitation based on air cushions or magnetic levitation systems. Both of these new systems minimize the concentrated loads which are transferred to their supporting structures, typically called "the guideway". There is a potential use for cold-formed light-gage metal elements and sheets in this booming transportation market and candidate designs have been developed and are presently under investigation.

One typical candidate design which is being investigated is shown in Figures 20 and 21. The main superstructure module is made from long thin hyperbolic paraboloid shells bounded with steel edge members that can be "nested" for economical shipping. Structural efficiency is further increased by composite action between the hyperbolic paraboloid shells and the light-gage steel used to form the channel-shaped structure which interfaces between the guideway and the vehicle.
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The variation in section depth from a very minimum at mid-span to a maximum over the pier, at which point hammerheads can be eliminated results in both an efficient structure as well as a very minimal overall profile which is aesthetically pleasing. Intrinsic to the geometric shape is the point support at the pier. This permits ease of application to curves and superelevations needed to accommodate a given route.

A variety of similar designs are possible such as having straight center sections with the tapered sections near the piers only or using expanded plastic cores on the exterior of the stressed-skin for both stiffening as well as for protection of the steel. A candidate concept using a light-gage triangular box section acting composite with a concrete slab is shown in Figure 22.

IV IMPLEMENTING NEW DESIGNS

The philosophy behind developing many of the designs shown is to keep the sophistication at the level of the design, analysis and technology utilized. The modules developed and the components used for construction should minimize sophistication needed in the field and permit simple construction with a minimum use of field labor and a minimum use of strict tolerances. Although many of the designs discussed above show unique geometries, much of this can be accomplished in an industrialized manner. You will note that many of the
modules that are developed result in straight line edge members permitting ease of connections. We are therefore developing new building components, the geometry and the analysis of which utilize state of the art technology with readily available materials. The construction and erection of these components, however, is directed towards simplifying and thereby reducing the cost of construction.

Development of stressed-skin components requires analysis with finite element techniques to properly evaluate the interaction of the shell geometries with their edge members as well as the interaction between different modules as was the case with the Place DeJardins project (Figure 7). However, finite element techniques should never be a substitute for understanding the continuum mechanics of stressed-skin structures based on classical shell theory. It is only through the latter that we are capable of evaluating the results of computer analysis based on finite element techniques.

We therefore recommend enough analysis of such structures by shell theory and closed form mathematical solutions, which will permit one to at least determine how he expects the structures designed to behave. This will assist in both developing the proper finite element model for more detailed analysis as well as evaluating the results obtained with it.
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V. REQUIRED RESEARCH

To continue the potential applications and implementation of cold-formed light-gage metal structures in the construction industry, research must be maintained. Research should continue in areas that would both benefit the design profession as well as the manufacturers of cold-formed components.

Research should continue in the area of stability analysis of light-gage metal shell components as this is the backbone for the potential use of free form lightweight steel structures. Analytical and finite element solutions for stability analysis of shell structures should be supplemented with research which determines the degree of sensitivity to local flat spots in shells, and the difference that one can expect from the mathematical curvature desired and the true curvature in the shell.

Research should continue in areas of developing methods of stiffening light-gage metal sheets. The common approach of utilizing flutes should be supplemented by seeking out continuous stiffening approaches such as the plastic foams and expanded plastics discussed in this paper. Research work is required to further determine the reliability of bonding such core structures to light-gage metal.
Research should continue in the area of connections for light-gage sheets. Present emphasis has been on welding techniques. Mechanical methods of fastening such as the use of small rivets similar to what has been used in aircraft structures should also be considered. I believe methods which could combine the benefits of both button punching and welding, for example, could have interesting possibilities of providing both strong as well as reliable connections.

In addition, I would encourage research at the design level to explore alternate concepts and approaches to utilizing light-gage metal shapes and structures to develop economical construction.

VI. CONCLUSION

This paper has shown a variety of applications developed at Lev Zetlin Associates, Inc. for the use of cold-formed light-gage metal structures in the construction industry. The applications developed to date show the potential for this type of construction to cut costs as well as to provide aesthetically pleasing functional designs. This has been accomplished in projects in the industry to date by keeping the sophistication in the design, the analysis and fabrication of components while providing rapid simplified construction techniques. The potential of light-gage metal should be further explored by the design profession as well as studied by industry.
Diaphragm Roof on Niagara Falls Convention Center

Decking Eliminates Cross Bracing on Long Span Arches
Clear Span of 400 Feet with Stressed-Skin Modules
Figure 5

Erecting Superbay Hangar Stressed-Skin
230 foot Modules
Figure 6
Readily Available Deck Forms
Hangar Stressed-Skin Roof
Figure 7

Hypar Module System For Mall Roof
Figure 8
Model of Prefabricated Hypar Module System
Figure 9

Domed Stadium with Shell Modules
Figure 10
Permanent Inflated Stainless Steel Membrane

Figure 11

Stressed-Skin Modules for Industrialized Building System

Figure 12
Pre-Engineered Stressed-Skin Metal Building

Figure 13

Pre-Engineered Maxi-Span Industrial Building

Figure 14
Hypar Module Symmetrical Framing System
Figure 15

Expanded Plastic Core Precludes
Shear Buckling of
Efficient Light-Gage Web
Figure 16
Light-Gage Steel Beam and Deck Components

Figure 17

Buckling Resistant Light-Gage Roof Module

Figure 18
Buckling Resistant Curved Skin Roof Module
Figure 19

Stressed-Skin Rapid Transit Guideway
Figure 20
Stressed-Skin Guideway with Light-Gage Vehicle Interface Structure

Figure 21

Composite Slab and Stiffened Skin System

Figure 22