

# PROBLEMS RELATED TO THE DESIGN OF METAL ROOF SYSTEMS

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**E**conomic advantages stemming from recent developments in production techniques, increased knowledge in the area of behavior and design of cold-formed steel structures, and the availability of design specifications have made thin-walled members popular in the building industry. While cold-formed sections may be used exclusively in small buildings, for larger buildings (such as those used for industrial, commercial and agricultural applications) both cold-formed and hot-rolled sections are combined to form economical and efficient structural systems. In 1964, pre-engineered metal buildings accounted for 24 percent of non-residential low-rise construction. By 1981, that figure had jumped to 56 percent. Competitive initial pricing, cost predictability, project completion time, reduced maintenance, and expansion flexibility have been major factors contributing to the exceptional growth of the metal building industry.<sup>1</sup>

This growth, however, has been overshadowed by an alarming increase in the number of metal roof failures.<sup>2</sup> In an editorial paper entitled "Winter Roof Collapses: Bad Luck, Bad Construction, or Bad Design?" in the December 1979 issue of *Civil Engineering*, Assistant Editor Ann Seltz-Petrash reported that there were more than 100 such failures in Chicago alone.<sup>3</sup> Referring to these failures, Harry Stavrides (Chief Structural Engineer, Building Department, City of Chicago) said, "Of the buildings that failed, a large portion were steel joist roofs and pre-engineered buildings."\*. A similar disturbing account is given by Zamencik<sup>4</sup> of 24 roof failures in Connecticut during the winter of 1978. Fifteen of these failures involved either steel joist construction or manufactured metal buildings erected after 1960. Sixteen of these 24 failures had a roof live-load of less than 30 pounds per square foot, the state building code minimum.

In a recent study carried out by King<sup>5</sup> at the University of Texas at Austin under the supervision of the present author, three main areas were identified as possible sources of the major problems associated with the reported failures:<sup>6</sup>

1. underestimation of the loadings that may be applied to a roof system during its lifetime,
2. lack of clarity in the current AISI<sup>7</sup> and AISC<sup>8</sup> design specifications dealing with the design of roof systems, and
3. poor quality of fabrication of the various structural components that make up a roof system.

Roof systems usually consist of built-up roof beams, cold-formed steel purlins and cold-formed steel panels which are attached to purlins to form what is commonly known as a shear diaphragm. Sag rods also may be used to carry the weight of purlins during construction. Thus, the structural integrity of a metal roof system depends not only on the performance of its individual components, but also on their interactive behavior.

The objectives of the present paper are to discuss briefly some of the design problems related to the interactive behavior of the various components that make up a roof system and to provide an account of the research efforts, both in the United States and abroad, which are aimed at resolving some of these problems. More specifically, the paper will address the following four areas:

1. problems related to the design of roof beams,
2. problems related to the design of purlins,
3. problems related to the design of roof panels, and
4. problems related to the design of connections between the various roof components.

## PROBLEMS RELATED TO THE DESIGN OF ROOF BEAMS

Metal roof systems usually are required to span over large areas and to provide column-free floor space. In this case, conventional hot-rolled sections are inadequate to support the applied roof loads. Instead, thin-walled built-up sections designed according to the AISC<sup>8</sup> Specifications are used. These design criteria, however, are based on experimental work involving relatively stocky flanges and slender webs, atypical of the sections used by the metal building industry. It is assumed, for example, that the bending moment is primarily resisted by the flanges and that the web mainly carries the shear. This is not the case, however, with sections used by the metal building industry where the web could carry as much as 70 percent of the bending stresses. Furthermore, in designing built-up sections, the AISC specification assumes that the flanges provide a high rotational restraint to the web and vice versa. That is, it is assumed that if local buckling takes place in either the flange or the web, the rotational restraint offered by the buckled component to the unbuckled component remains intact. More specifically, it is assumed that the buckling coefficient ( $K$ ) for the flange is 0.7, a value halfway between the simply supported case ( $K = 0.425$ ) and the fixed condition ( $K = 1.277$ ). In the case of the web, a value of  $K = 39.6$  is assumed, which corresponds to 80 percent fixity along the flanges.

A theoretical study conducted by Shehata<sup>9</sup> in 1977 at the University of Texas at Austin showed that if both the flanges and the web have a high width-to-thickness ratio, buckling of one element will induce simultaneous buckling of the other. The premature failure of either the flange or the web will result in a reduction of the ultimate capacity of the member. This was later substantiated with tests conducted at the University of Texas at Austin<sup>10</sup> involving several tapered and prismatic girders typical of the ones used by the metal building industry. It was shown in these tests that the safety factor, defined as the ratio of the ultimate capacity of

the members to the allowable load as determined through the AISC specification, was considerably lower than 1.67.

Based on the results of these tests, it was concluded that the AISC design criteria are not conservative for sections typically used in pre-engineered buildings. These results clearly demonstrate the need for a critical examination of the present AISC specification requirements as applied to these built-up sections.

### PROBLEMS RELATED TO THE DESIGN OF PURLINS

Although cold-formed steel members, such as channels and Z-sections, provide substantial savings due to their high strength-to-weight ratio, their cross-sectional configuration gives rise to behavioral phenomena which are not encountered in the more familiar symmetrical sections. Of great concern to structural engineers is the tendency of these members to twist under most conditions of loading and to fail by yielding or local buckling as a result of the stresses developed. Thus, strength as well as serviceability criteria should be taken into account in the design of these members.

Purlins, however, are attached along one side to the wall or roof panels, and in many installations, are supported along their span by sag rods. Thus, some degree of restraint against the lateral and rotational displacement of these members is always present.

Before 1980, there was no provision in the AISI design specification to account for the restraining effect of the attached wall or roofing material on the behavior of the girts or purlins. In the 1980 edition of the specification, however, the AISI included the following clause:

*Channel and Z-sections used to support attached covering material and loaded in a plane parallel to the web shall be designed taking into account the restraining effects of the covering material and fasteners.*  
(Clause 5.3.1, AISI 1980 Specification)

This specification, however, provides no guidelines for the quantitative evaluation of these restraints and no method is given which accounts for such restraints in design. Without any guidelines, the designer often makes ostensibly safe assumptions which may neglect the presence of bracing altogether. Such is the case in wall or roof assemblies under negative pressure (suction) where the girts or purlins are attached to the wall or roof material along the tension side. If the tension flange connection is ignored, overly-conservative designs may result.

The difficulties related to the analysis and design of braced-channel and Z-section purlins have become of great concern to both designers and manufacturers of light industrial buildings. This concern was reflected in the priority recently given to this area by the AISI's Cold-Formed Advisory Group. As reported at the Sixth International Specialty Conference on Cold-Formed Steel Structures held in St. Louis, Missouri, on November 16-17, 1982,<sup>11</sup> this advisory group established a rank order for proposed areas and topics for specification revision. In reviewing 54 items which were considered essential areas for research, the area of channel and Z-section behavior was ranked second in priority. The area of braced purlins has been the focus of investigation by several researchers in the United States,<sup>12, 13, 14, 15, 16, 17</sup> in Canada,<sup>18, 19, 20, 21</sup> in the United Kingdom,<sup>22, 23,</sup> and in Sweden.<sup>25</sup> The results from these investigations,

however, tend to be complex in form and difficult for use in a design office. Future research should be directed toward simplification of existing analytical techniques rather than developing new ones.

The importance of sag rods in roof systems has not been well understood by engineers and fabricators. Scarlett<sup>26</sup> points out,

*"Sag rods help to guarantee the structural efficiency of the completed roof under adverse conditions, particularly wind uplift, for little extra cost. There is a danger, however, that due to pressures from 'sales' for overall price economies, the importance of such members may be disregarded."*

In a recent study<sup>19</sup> it was shown that sag rods, if properly applied, may act as discrete bracing, and thus provide full support against displacement of channel and Z-section purlins. In practice, however, the use of sag rods as a bracing device is often rejected on the assumption that the steel panels, once erected, provide adequate lateral restraint to the purlins.

The question, therefore, on the importance of sag rods as restraint agents in roof systems still remains. Research in this area would provide a better understanding of the bracing requirements of purlins, and could result in considerable savings in the fabrication of metal roof systems.

An important consideration in the design of cold-formed sections is also the width-to-thickness ratio of the compression elements. Because cold-formed sections are very thin, local buckling of individual elements rather than yielding may govern their load-carrying capacity. The magnitude of the applied load depends not only on the width-to-thickness ratio but also on the edge condition of the compression elements. Greater compression stress is permitted in flanges if a lip acting as a stiffener is provided along one edge of the flange. If, during the forming of the section, either this lip stiffener or the angle between the flange and the stiffener is made too small, the compression flange may act as an unstiffened element with a possibility of failure at much lower stress than assumed.

Present specification requirements for the design of stiffened compression flanges are based on research where lip stiffeners at 90 degrees were used.<sup>27</sup> In most sections used as purlins, however, the angle between the lip stiffener and the flange is less than 90 degrees. Further research is required to determine the effect of lip stiffeners which are not perpendicular to the compression flange.

An additional problem related to the design of purlins is the effect of "nesting," a method used to provide continuity of Z-section purlins. If variations on the cross-sectional characteristics of the nested purlins exist, additional twisting of the members caused by lack of fit may take place. If these rotations are not taken into account during design, the member chosen may not be adequate to resist the applied loading.

### PROBLEMS RELATED TO THE DESIGN OF ROOF PANELS

Roof panels usually consist of cold-formed corrugated sheets of metal and serve three main functions:

1. they resist vertical (gravity and uplift) loads,
2. they resist lateral (wind) loads, and
3. they provide lateral and rotational support to the purlins.

The effectiveness of roof panels in resisting lateral (wind) loads depends on the shear rigidity of the roof system. Roof systems which are designed to resist lateral loads are called shear diaphragms.

Although significant progress has been made towards developing theoretical models for determining the shear rigidity of diaphragms,<sup>26, 27, 28, 29, 30</sup> the most commonly used methods remain experimental.<sup>31, 32</sup> Such methods, however, are costly and time consuming. Simplification of the theoretical models would certainly provide the engineer with a valuable design tool.

In the design of roof shear diaphragms it is important to include their effectiveness as lateral and rotational restraints to the purlins. The degree of restraint provided depends on the cross-sectional properties of the panels, the span along the corrugations and the type and spacing of the fasteners. The amount of lateral restraint is directly proportional to the shear rigidity of the diaphragm, while the amount of rotational restraint is a function of the rotational stiffness of the diaphragm. Although the behavior of channel and Z-sections attached to shear diaphragms has been extensively investigated, the difficulty in determining values to be used in design calculations for both the shear rigidity and the rotational stiffness of diaphragms has been the major shortcoming of these methods.

## PROBLEMS RELATED TO THE DESIGN OF CONNECTIONS

In the design of metal roof systems, connections play a very important role. The type of connection chosen and the method of attachment used may significantly affect the behavior characteristics of the roof systems, and the overall cost of the structure. The problems related to the design of connections between individual panels, between panels and purlins and between purlins and the main roof beams will be critically discussed in the following sections.

### Panel-to-Panel and Panel-to-Purlin Connections

The ability of a roof system to act as a shear diaphragm depends not only on the cross-sectional configuration and length of the panels, but also on the fastener type and the methods used to stitch the panels, but also on the fastener type and the methods used to stitch the panels together and to fasten the panels to the purlins. The fasteners must be capable of transmitting shear between the purlins and the panels with relatively little slip, but they must also permit short-term movement caused by temperature changes. However, these requirements are incompatible. Attempting to fix the wall or roof panels by means of a sliding clip, thus ensuring movement of the panels, might render the roof system ineffective as a shear diaphragm. In this case, the degree of restraint which the panels provide to the purlins is questionable, and alternative types of lateral support must be designed.

Roof systems must also be designed to resist vertical loads. Of special importance is the effect of wind uplift. Wind presents particular problems on the windward eaves of low-rise buildings.<sup>33</sup> As a result, several collapses<sup>34</sup> have taken place, triggered by localized failures in the ends of the structure. A serviceability problem, attributed to wind, is also the formation of floating air between roof panels, a situation which could potentially result in roof leakage. Thus, special care should be taken when estimating the wind

load effect at corners and when designing the connections to ensure that the panels are appropriately anchored.

A recent investigation was coordinated by this author<sup>34</sup> at the University of Toronto in order to determine the degree of rotational restraint which the roof panels provide to the purlins. In this investigation, two full-sized systems consisting of cold-formed Z-sections and steel panels were tested to failure under suction. In the first specimen, the panel-to-purlin fasteners were located at midflange of the Z-section. Under loading, the Z-sections rotated, placing the heel of the section in direct bearing against the panel. This arrangement of the fasteners gave rise to a rotational restraint which helped reduce the overall rotation of the members. In the second specimen the fasteners were located very close to the heel of the Z-section and thus a rotational restraint did not develop. As a result, large displacements of the members at very low pressure took place. Present design specifications require that adequate bracing be provided to limit the rotation of asymmetrical sections and sections which are subjected to eccentric loading. This procedure, however, is overconservative since it does not take into account the restraint provided by the roof panels.

### Connection of Purlins to Roof Beams

Traditionally, the development of theoretical models for the analysis of purlins has been based on the assumption that neither lateral nor rotational displacement takes place at the supports. Research by this author,<sup>35</sup> however, has shown that the types of connections used by the building industry to connect purlins to roof beams do not provide complete restraint against rotation of the members at the supports. Quantitative evaluation of the degree of restraint present at the supports is essential for the design of purlins. A research project is currently being conducted at the University of Texas at Austin on this problem.

## CONCLUSIONS

Although considerable research has been directed toward the behavior of roof components and roof systems, a significant number of problems still exist in the design of roof systems. Some of these problems are caused by a lack of design guidelines, which has prompted designers to make assumptions that are not always safe and which can lead to serious strength and serviceability problems in the structure. Other problems are caused by the quality of engineering design and fabrication. As Zamencik<sup>3</sup> indicates:

*"The types of problems encountered in metal roof systems are not to be typical of all construction employing cold-formed steel members, but are simply indicative of the fact that the detailed design considerations for such members are not always well understood by those attempting to utilize the economy of this material."*

Zamencik's concern over the quality of the engineering design and fabrication is not unfounded. Published information<sup>36</sup> has shown that a number of serviceability and strength problems in pre-engineered buildings can be avoided if engineering design and fabrication techniques are improved. This requires the cooperation of researchers, engineers and fabricators as well as a commitment by the building industry to actively support research efforts aimed at resolving these problems. The present paper highlights some of the major problems that need to be addressed in order to develop safe and more economical roof systems.

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