Lower Cost Lightweight Cold-formed Portal Frames

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LOWER COST LIGHTWEIGHT COLD-FORMED PORTAL FRAMES

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ABSTRACT: Southern Africa has a dire need for housing small industries and people, and concomitantly the creation of employment. It is common to use hot-rolled steel sections for industrial structures, which are pre-manufactured and then bolted together on site. In this paper an alternative structural concept for low-rise portals for light industries is proposed, whereby the total frame is made up of standard cold-formed sections which are cut and welded together on site. The cladding material is employed as an integral structural component through the principles of stressed skin diaphragm action. A short pile footing is proposed to provide a degree of rotational fixity for the columns of the frame. Different frame configurations are investigated and the practical application of the concept is discussed.

INTRODUCTION

Although certain developed metropolitan areas exist in Southern Africa, vast areas are underdeveloped and in need of light industries, houses and community buildings. This part of the world is consequently in dire need of the creation of employment and the development of skills.

Southern Africa has no significant natural forests, and timber for structural uses (amongst others) come from plantations or has to be imported. Iron ore reserves and developed steel industries, producing hot-rolled and cold-formed steel sections, do however exist in this region.

Other than in the coastal areas, structures are not subjected to severe corrosive atmospheres. The design code prescribed imposed loading on structures at 6,3 lb/ft^2 (or 0,3 kPa) and the wind loading (1 in 50 year wind speed is 130 ft/s or 40 m/s), are comparatively low.

Given the above needs and requirements under prevailing conditions, this paper proposes the use of cold-formed steel sections in an alternative and economical construction method for the framing of light industries, community buildings and houses.

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THE NEED FOR INNOVATIVE LIGHTWEIGHT STRUCTURES

A process of structural adjustment in the developed market economy as well as a reconstruction of its less developed socio-economic framework is required to achieve equitable access of all Southern Africans to all opportunities in the economy of the area. Historical development patterns of newly industrialising countries would suggest that the primary contributor to economic growth and employment creation will need to come from the expansion of the manufacturing sector. Basic strategies should be aimed at increasing the number of independent small and medium sized manufacturing enterprises and expanding their share in the Gross Domestic Product.

To sustain an efficient market driven manufacturing industry, the productivity of capital investment should be significantly increased. The initial capital outlay in the establishment of an industrial infrastructure, specifically the construction of the factory building should be kept to a minimum. The employment creation in the construction of such, need to be pursued in an alternative and innovative way within the context of a developing country.

The most suitable facilities for small to medium industrial enterprises are the popular 'mini-factory' complexes. In general terms, a mini-factory can be best described as a rentable industrial structure, approximately 700 to 2000 ft^2 (200 to 600 m^2) in total floor area, not designed to meet specific client requirements, i.e. it should be so simple in layout that it may be adaptable to suit almost any manufacturing or storage requirement. However, in general it seems that conventional developments are constructed of building materials and to facades to achieve high aesthetic qualities, in contrast to the plain and simple purely functional structures believed to be required (and are able to be afforded) by the developing sectors of this area.

In addition, Southern Africa has to contend with a severe housing shortage due to a high population growth rate, urbanisation and rising expectations. The housing backlog runs into millions of units. Major socio-economic programmes are needed to boost development in the residential developing communities. In recent years, there has been a marked shift in housing policy - away from exclusive state responsibility in many categories to a self-help approach, known as incremental housing. One such system could be to provide the new owner with a roof and a supporting frame. The roofing structure may be completed by small contractors and the infill and exterior walls constructed either by another contractor or by the 'self-help' principle of owner involvement.

CONVENTIONAL INDUSTRIAL STRUCTURES

The present construction and project management systems employed in the 'mini-type' or smaller industrial establishments are basically the same as for the larger industrial concerns. Only the end product is smaller. Large development institutions employ architects and project planners to detail 'mini-type' factory complexes that are suited to the general small industrialist or warehouse facility by way of long-term lease agreements. Although these complexes are usually aesthetically pleasing in that it reflects the present architectural trends, high building costs are incurred by unnecessary complicated architectural details.

Engineering input is usually required after the basic architectural layout has been finalised with the client. The common use of hot-rolled steel sections for these structures, as for the large industrial buildings, result in the necessity of appointing a specialist contractor. The requirement of shopdrawing details, specialised engineering workshop manufacturing of frame components as well as specialised erection crews, all contribute to the relatively high cost of erecting the building. Presently in Southern Africa, no use is made of cold-formed steel for the construction of the portal frames of industrial type buildings.

ALTERNATIVE CONSTRUCTION STRATEGY

The major industrial building project costs are incurred in the last step in the chain of events, i.e. the construction of the mini-type factories. A great component of the construction cost lies in the skilled labour and the expensive equipment employed on the site. In an attempt to reduce on both these components as well as to create employment for the unskilled labour sector of Southern Africa, a total new approach needs to be considered. One such approach could involve the following:

- The use of only one or two skilled welder artisans on site, and the rest of the crew comprising unskilled labour,
- The total structure welded together on site, in contrast to the traditional use of bolted connections,
- Steel thickness in the order of 0.08 to 0.10 in. (2.0 to 2.50 mm) to result in adequate welded joints, but also to retain low component mass for manhandling on site,
- Employment of mostly standard commercial steel section lengths to save on wastage incurred costs,
- The only equipment required on site will therefore comprise: welding/generator plant, angle grinder, hand drill, lightweight movable scaffold.

If steel portal structures for mini-type factories can be constructed to the abovementioned limitations, it would further have the following cost saving implications:

- No engineering shopdrawings would be required, as the total structure may be cut and welded together on site. Normal structural drawings would still be required,
- No manufactured elements by specialist engineering enterprises need be made up,
- No site crane required,
- No specialist erection crew required,
- More simple, probably empirical, design methods by structural engineers,
- If these structures could be standardised to an extent, the architectural and quantity surveyor inputs can moreover be minimised.

DESIGN APPROACH

Given the above parameters to design alternative, more economical lightweight steel portal structures, it follows that commercial cold formed steel sections or components made up of such would be best suited for the entire structure. This would further implicate an alternative approach to the design of the structure as a whole, in contrast to the conventional building methods wherein each individual part of the structure is designed to be structurally sound in its own right, and usually not interdependent on other elements for its own integrity.

The germ of the proposed design approach can best be described as a monocoque principle analogous to an exoskeleton structure. This would implicate that the total three-dimensional structure be designed as a single module, as opposed to the sum of individual components. To accomplish this, the principles of stressed skin diaphragm action through the cladding material have to be considered in the design process.

The most notable limitation of open cold formed steel sections is the lack of torsional stiffness. The low torsional stiffness of an open section makes it susceptible to early lateral torsional buckling under bending moment induced loads. One way to overcome this handicap is by stitchwelding two open lipped channel profiles together, thus creating a closed torsional cell rather than the weaker open section. (See Figure 1)

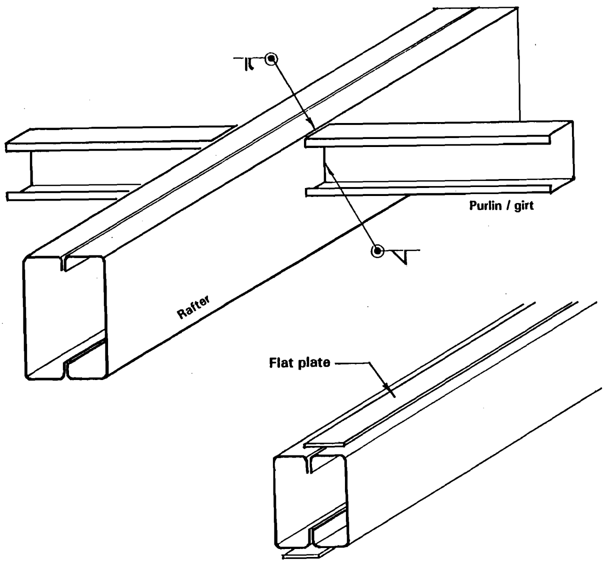


FIG. 1. Lipped Channel Tube and the Strengthened Tube

Bearing in mind the principles of stressed skin diaphragm action through the cladding material in simulation of an exoskeleton structure, it would be beneficial to place the purlins and girts in the plane of the portal frames (see Figures 1 and 2). This would reduce eccentricity in stress transfer between cladding, purlins and frame elements. In addition, this has two added advantages, the first being the increase of bending stiffness of the purlin/girt in its joint fixity at the portal frame.

The degree of fixity at the portals is however related to the torsional stiffness of the portal frame section, specifically for the gable portal frame. The second advantage of this fixing method is the introduction of a torsional support to the portal frame at purlin fixing positions (Rhodes and Walker, 1979). This torsional support stiffness is in turn related to the bending stiffness of the purlin about its main axis of gyration. Thus by the fixing method employed between the purlins and the portals, an interdependency is created through the principles of loadsharing.

In contrast to the cladding material being used only as a means against the weather elements, it should be employed as an integral structural component. By positive connection to the remainder of the structure, the cladding material may act as a deep diaphragm beam spanning between gable portals. With empirical data on the diaphragm shear stiffness of the most common cladding profiles known, the stressed skin analytical principles can further be used to obviate the use of traditional cross-bracing, by transferring shear stress through the cladding material.

PROPOSED METHOD OF ERECTION

Given the simple proposed structural layout and the low individual mass of structural components, a typical mini-type factory installation may be erected as follows:

1. Mark out and excavate footings to portals, (the most appropriate footings for this structural system are discussed in a following paragraph),
2. Place portal columns in footing excavations, and ram in dry concrete mix,
3. Weld portal rafter sections together on site, laid flat on an even surface,
4. Man-handle rafter sections into position with the aid of lightweight scaffolding, and clamp to the column sections, before welding the eave joints,
5. Weld in standard length purlins and girts, (in the plane of the rafter sections),
6. Fix cladding material and finishes. (It is preferable to support the structure during fixing of the roof cladding material),
7. Cast internal concrete surface bed slab.

Due to the simplicity of the structure, and the concomitant simplicity of the erection thereof, valuable construction time may be saved, incurring even greater savings in total project costs. In addition, the relative low structural component mass would result in saving in transportation costs, a factor of significant implication for industrial development far removed from the main steel supply centres.

DIAPHRAGM ACTION

Certain demands are made on structural element interaction for the proposed alternative lightweight steel portal structures. In the endeavour to achieve structural element interaction related to an exoskeleton structure, the employment of the principles of stressed skin diaphragm design calls for particular prerequisites in the structure composition.

The benefits of stressed skin diaphragm action only became apparent over 35 years ago when tests on actual buildings revealed stresses and deflections considerably smaller than those predicted by conventional design calculations (Davies and Bryan, 1982). The nature of these buildings, i.e. factory or warehouse type structures without internal floors, was such that the enhanced performance could only be attributed to the beneficial effect of the profiled steel sheet cladding.

It is therefore evident that the consideration of the stressed skin diaphragm action provided by the cladding material would describe the true behaviour of the completed building more accurately than the idealised behaviour of the frame alone. As steel becomes increasingly expensive, the neglect of the significant contribution to performance by the cladding material would constitute a waste of a valuable asset.

Stressed skin diaphragm design is comprehensively described by Bryan and Davies (1992) and Davies and Bryan (1982). De Vos (1996) outlines in detail and De Vos and Van Rensburg (1996) briefly describes the application of the abovementioned principles and procedures in the context of the structural concept proposed in this paper.

FOOTINGS

It is conventional to use pad type footings for steel buildings. These footings must be accurately positioned; grout under the base plate may compensate for small inaccuracies in height and pockets around the holding down bolts can allow for small discrepancies in plan positioning. For a light single storey building it is uneconomical to design the pad footing for any significant degree of moment fixity in the column base.

Short pile footings, which may readily be used in the construction method outlined in this paper (see Figure 2), was found to be more appropriate to provide a degree of moment fixity to the base of a lightly loaded column.

De Vos (1996) investigated the behaviour of lightweight single storey portal frames founded with short pile footings in various typical soil conditions. At least fifty percent of the fully fixed support moment can easily be achieved with the short pile footing. The degree of rotational fixity of the support thus increases the stiffness and stability of the frame.

LIPPED CHANNEL TUBE SECTIONS

In consideration of the cold-formed sections in line with the proposed construction method, the first choice would be the torsionally stiff sections, i.e. square and rectangular tubing sections. It was found however, that in Southern Africa these sections are very expensive in relation to other cold-formed sections (based on average cost per mass, the square tubing profiles are approximately 20% more expensive than lipped channel tube sections) and only a limited range is commercially available in Southern Africa.

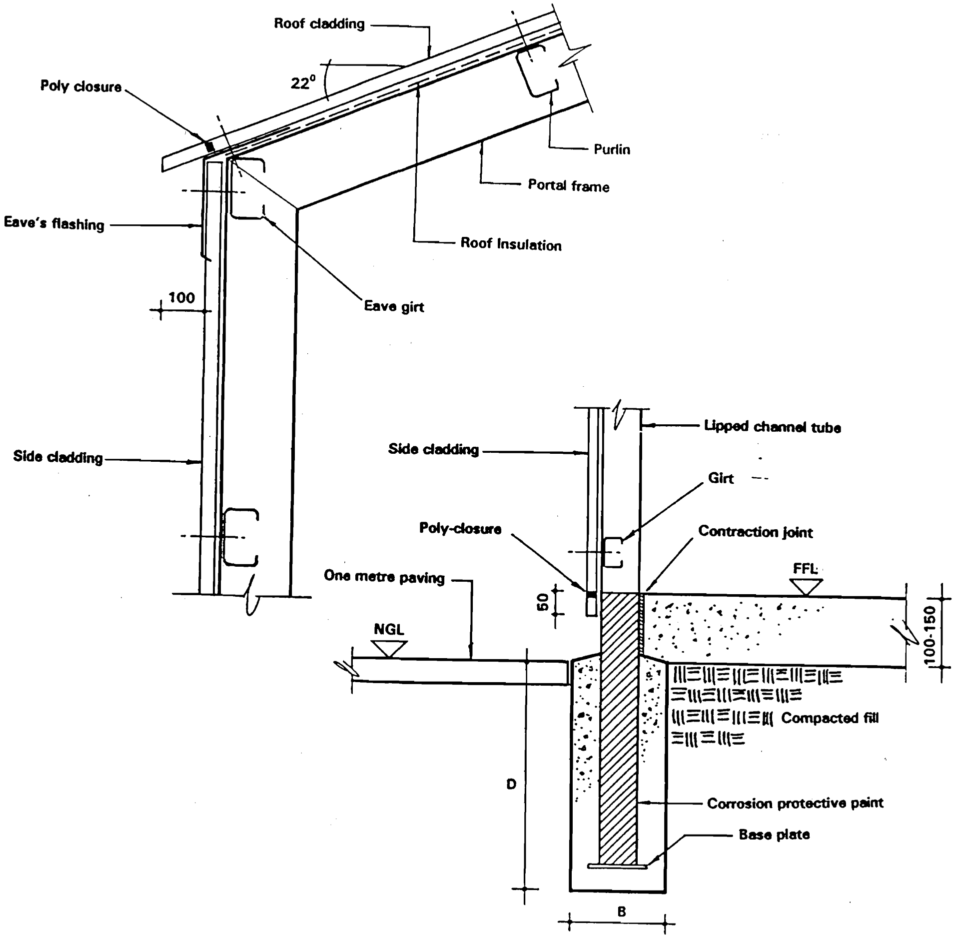


FIG. 2. Typical Footing, Frame and Eave Details

As all cold-formed steel profiles (bar the tubing previously mentioned) are open sections, high torsional stiffness may be achieved by a section made up of commercially available profiles. A great variety of rolled cold-formed sections are available. In fact, based on a minimum required order, just about any form may be rolled by certain steel profiling establishments.

Many innovative cold-formed profiles are used in the construction industry. A few examples are mentioned here. The British Swagebeam (Trebilcock, 1994) system has been developed primarily as a portal frame system for the modest span market (up to 14 m). Swagebeam buildings are delivered to site with sections cut to length and with connection holes pre-punched at the factory as part of the computer controlled manufacturing process (Kirk, 1986). The Lightweight Steel Framing system developed in Canada (Trestain, 1988) for mainly the domestic market, is manufactured with regularly spaced holes in the webs to serve as raceways for electrical and plumbing lines.

In application with the proposed construction method, a wide range of sections made up of various standard cold-formed profiles were investigated with regards to cost and commercial availability in Southern Africa. The cost of new unique profile shapes (minimum of 3 tonnes order per size) does not relate well to the more standard commercial profiles, making it impractical for the proposed low-cost structural concept under investigation.

The most common cold-formed profile type in South Africa, with a wide range of sizes commercially available, and reasonably priced, in terms of bending stiffness to weight ratio, is the lipped channel section. Lipped channel profiles may be utilized to make up more stiff sections. Creating a tube with two lipped channel sections as per Figure 1 results in an element that is easy to handle on site. This section is aesthetically pleasing and has a high degree of torsional stiffness (generally over 4 000 times more than the open section).

The creation of lipped channel tube sections, in the factory, or on site is a simple operation requiring a few clamps and then stitch-welding at specified spacings. Composite tube sections have been extensively used in practice, specifically in the construction of carports and related structures.

Techniques to increase the bending stiffness of a given tube without serious cost implications were investigated. These techniques could then be utilized in applications that would require elements with a stiffness that lies between that given by tubes made up of standard commercially available profiles or at specific locations in the frame, such as peak bending moments. One method to enhance the bending stiffness of a tube element which has proved to work well, is by welding flat steel plates onto the flange sections of the profile as per Figure 1.

COMPUTER MODELLING

The typical portal structure with rigid-jointed steel frames and cladded with profiled steel sheeting was modelled by De Vos (1996). Such a structure has two distinct load carrying systems. Part of the load is carried by frame action in the conventional way and part is carried by diaphragm action in the cladding. The distribution of load between the frames and the cladding is dependent on their relative stiffnesses.

The elastic analysis of a complete exoskeleton structure is therefore a matter of satisfying the requirements of compatibility between the frames and the sheeting. This requires an analysis which considers the complete three-dimensional structure. The three-dimensional prototype portal structure was firstly analyzed without the benefit of simulated stressed skin diaphragm action and secondly with the benefit of stressed skin action. The latter gave an indication of improved performance of the structure in simulating the actual performance of such.

In the computer simulation of stressed skin action, the individual portal frames are connected together by complete sheeting panels of which the shear flexibility is summarised by a single quantity. As these cladding panels provide, in effect, a simple coupling between adjacent frames, precisely the same coupling may be obtained by replacing the shear panels by 'springs' of the same flexibility (Davies and Bryan, 1982).

The computer model for the portal building is shown in Figure 3 and consists of six individual elements, i.e.:

(1) Portal column section
(2) Portal rafter section
(3) Purlin/girt section
(4) Gable column section
(5) Cladding prismatic section
(6) Cladding shear panels - simulated as 'spring' elements.

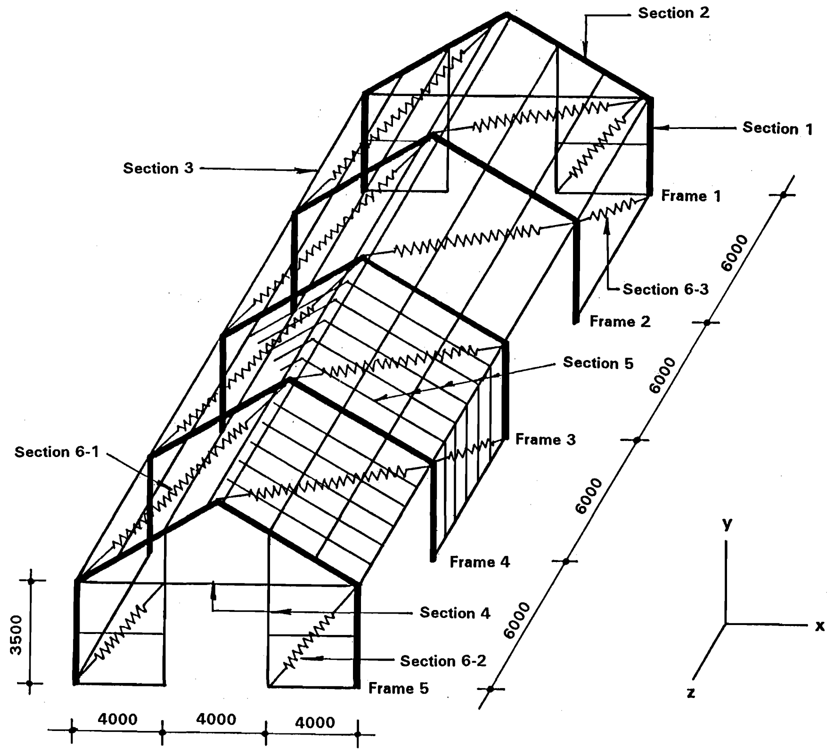


FIG. 3. Computer Model for Portal Structure

The first five elements constitute the conventional rigid frame sections and the last panels represent the stressed skin diaphragm action.

For the purposes of analysis the following sections were chosen for the portal structure:

- Section 1 Portal column: 2 No 175 x 50 x 20 x 2 mm (2 No. 7 x 2 x .8 x .08 in.) lipped channel tube
- Section 2 Portal rafter: section 1 + section 5 (The rafter section assumed the same as for the column section, to which is added the proportional section of the prismatic cladding section positively fixed to it)
- Section 3 Purlin/girt: 125 x 50 x 20 x 2 mm (5 x 2 x .8 x .08 in.) lipped channel
- Section 4 Gable column: 2 No 100 x 50 x 20 x 2 mm (2 No. 4 x 2 x .8 x .08 in.) lipped channel tube
- Section 5 Prismatic cladding: 0.60 mm (0.024 in.) IBR (Inverted Box Ribbed profile) x 1000 mm (40 in.) wide
- Section 6 Cladding panel: stressed skin diaphragm action simulation:

Three distinct shear panels can be identified from Figure 3 i.e.:

(a) Roof cladding panel - section 6-1
(b) Gable cladding panel - section 6-2
(c) Side cladding panel - section 6-3.

For the purposes of initial analysis the shear diaphragm panels were assumed to include the following common fixing methods:

- ϕ 6.30 mm (0.25 in.) self-drilling, self-tapping screws with neoprene washers in every IBR trough at the top and bottom perpendicular (purlin) members and every alternate trough for intermediate purlins,
- ϕ 6.30 mm (0.25 in.) self-drilling, self-tapping screws with neoprene washers into parallel (rafter) members at 250 mm (10 in.) centres,
- ϕ 4.80 mm (0.19 in.) aluminium rivets at 250 mm (10 in.) centres at cladding overlaps.

The individual shear flexibility components of the diaphragms were calculated according to the methods suggested by Davies and Bryan (1982).

A considerable reduction in bending moments and deflections under consideration of the stressed skin diaphragm action is evident from analyses (De Vos 1996). Some reductions in bending moments and maximum deflections are given in Table 1 for frame #3.

Table 1. Reductions in bending moments and deflections for frame #3 with consideration of stressed skin action

Load Combination	BM at base	BM at eave	$\Delta_{x(max)}$	$\Delta_{y(max)}$
C1:LL+DL	21%	20%	27%	21%
C2:DL+WL	57%	45%*	50%	24%

* average for the two eaves

Because the roof pitch is less than 45° (22° in this case), the effect of stressed skin action is more notable under mainly horizontally applied loads, such as wind load. The overall reduction in bending moments and deflections of the total structure, regarding the effect of stressed skin diaphragm action, strongly confirms the inclusion of such in the design process.

Consideration should be given to providing an effective midspan support to the diaphragm (in buildings of seven or more frames) by increasing the stiffness of only the midspan frame. An eaves-tie element on the midspan portal would significantly increase its overall bending stiffness with little cost implication. This would in effect provide a flexible (spring) support to the diaphragm, thereby increasing its contribution to the total structural performance.

Giving cognisance to the sensitivity of the stressed skin diaphragm shear stiffness to the way in which it is fixed to the structural components, it may be concluded that the most economical cladding fixing method, would involve fixing the cladding to the top and bottom purlins in every trough and to intermediate purlins in alternate troughs. Seam fasteners and sheet to rafter fasteners may be reduced to 500 mm (20 in.) centres as opposed to the 250 mm (10 in.) centres used in the analysis.

JOINTS

The objectives for the rigid joints were as follows:

- All joints should not only be simple to construct, but should in addition be economical in terms of material cost and labour time.
- The joints should be such that a versatile construction procedure may be possible. In other words, the joint details should not prescribe construction sequence.

Contrary to normal practice, no use is made of bolts on site, in any connection. All joints are site welded. Assuming coded site welding by a qualified artisan, the joints should also comply to appropriate design standards.

Overall economy in welded connections is difficult to evaluate. Some of the factors to be considered, such as the amount of electrode material used can easily be computed, while other factors such as the value to be placed on aesthetics may be intangible. Welded connections are usually neater in appearance, providing a less cluttered effect, in contrast to bolted connections. The actual economy of welded connections must consequently be viewed from a broad aspect and include the overall design of the structural system.

The portal eaves joint is usually the most highly stressed joint under any loading. The strength of the portal frame will in most cases be determined by the bending moment peak at the eave joint, implying the importance of this joint for the overall structural strength. For smaller span portals the simple welded eave joint as portrayed in Figure 2, would suffice.

The creation of the eave joint on site is a simple operation. After the eave level has been determined, the joint position is marked on the column and the rafter elements. These elements are then cut to the required angle, clamped in position and welded around. The simple welded eave joint offers the following advantages:

- Measurement can take place on site, no pre-cut elements are required,
- When welded around, the section is closed to water ingress,
- The joint is aesthetically pleasing, being of uniform section,
- No joint elements protrude beyond the section dimensions, in consideration of the purlin/girt elements that have to be welded on later,
- With a full penetration weld all around, the full section strength is transferable between the rafter and the column elements.

The bending moment is at a maximum at the eave of the portal. It is usually more economical to use a lighter portal frame section, and then to increase the section strength at the eave. Various means are at one's disposal to strengthen the portal section at the eave, the most popular being the introduction of an eaves knee or haunch.

Although significant strengthening of the section is possible with the introduction of an eave haunch it is disadvantaged by the following:

- The haunch encroaches into the clear headroom,
- The creation of the haunch is labour intensive and time consuming,
- It is usually not aesthetically pleasing, detracting from the clear line of the portal frame,
- Too much unsymmetrical welding onto the thin lipped-channel tube sections is likely to induce excessive residual stresses in the elements.

From an aesthetical and practical point of view, the section may also be strengthened at the high bending moment area at the eave, with the introduction of flat plates welded onto the flanges of the lipped channel tube section and illustrated in Figure 1. It is a very simple and fast solution for enhancing the section strength at the eave joint.

Although apex joints are not as highly stressed as the eave joints at a roof pitch of 22°, the normal simple joint may be strengthened by strapping with flat plates, similar to that suggested for the eave joint.

Simple short pile footings were proposed. See Figure 2. As the portal columns are simply placed in the excavated holes, a base plate to the column section is required. The dimensions of the base plate should be adequate to provide for bond to the footing concrete, but not to large to cause a void under such when concrete is placed. A void under the base plate would however be unlikely, as the dry-mix concrete is rammed into the footing. It is important to provide adequate corrosion protection to the column base, before placing it in the footing.

The joints between the purlins/girts and the portal frames were assumed to be rigid in the analysis. To accommodate this, as well as to provide lateral torsional support to the portal rafter at purlin spacings, it was decided to place the purlins in the plane of the portal frame as depicted in Figure 1.

In most cases it would be found that welding only the top and bottom flange sections of the lipped channel purlin/girt onto the rafter element would be sufficient to assume rigidity at the joint.

DIFFERENT FRAME CONFIGURATIONS

The construction and fabrication procedure lends itself readily to different frame configurations. The addition of horizontal roof elements or columns reduce the bending moments and deflections as outlined by De Vos (1996).

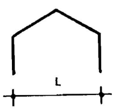
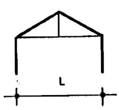
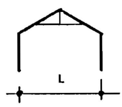
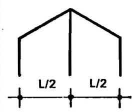
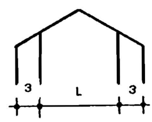
The forces and bending moments were determined for five different portal frame layouts. The analyses were conducted under the following assumptions:

- Roof pitch of 22°,
- Practical eave height of 3.5 m (11.5 ft.),
- Building to consist of 5 frames of which the centre frame (No. 3) is analyzed,
- Roof cladding diaphragm shear flexibility calculated in accordance with Davies and Bryan (1982),
- Frames in the building at 6000 mm (20 ft.) centres, (standard commercial steel length for purlins),
- Imposed vertical load over total area of 0.30 kPa (SABS 0160, 1989).
- Wind loads after SABS 0160 (1989).

First the single bay portal frame was designed and then certain structural elements were added as shown in Table 2. Two practical portal tie elements are in general use in South Africa. The horizontal eaves-tie is mostly used in domestic type portals where a ceiling has to be installed. Where no ceiling is required, a horizontal roof-tie, between the eave and the ridge of the portal, is often used in industrial type structures. For this investigation, only a king-post strut from the ridge of the portal was provided to these ties.

For the case of the single bay portal with an eave's tie, the eave tie and king-post were not loaded with ceiling loads and were assumed to have a bending stiffness half that of the main portal frame. The spans for different portal configurations are shown in Table 2.

TABLE 2. Portal Spans in meters for Sections (No Strapping)

Lipped channel tube section Two channels	 L	 L	 L	 L/2 L/2	 3 L 3
100x50x20x2	6.3	10.1	7.5	9.6	7+6=13
125x50x20x2	7.4	11.7	8.7	11.2	7.7+6=13.7
150x50x20x2	8.4	13.2	9.8	12.7	8.5+6=14.5
175x50x20x2	9.4	14.4	10.9	14.3	9.6+6=15.6
200x75x20x2,5	13.3	>18.0	15.0	18.1	14.3+6=20.3

As the employment of the eaves tied portal is more associated to the domestic housing and 'clean' industrial building types, it is disadvantaged by a deprivation of clear headroom in other industrial applications. The introduction of a roof-tie element, between the ridge and the eave of the portal results in notable reductions in maximum portal frame bending moments but does not severely intrude into the clear headroom.

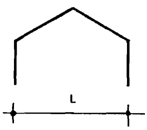
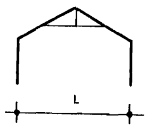
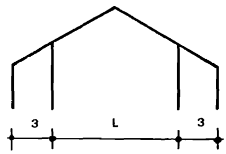
For the purposes of analysis, the roof-tie was placed midway between the eave and the ridge of the portal rafter and subjected to the same loading as for the preceding portals. The roof-tie and king-post were not loaded (other than its selfweight) and were assumed to have a bending stiffness half that of the main portal frame. The results are shown in Table 2.

Two dual-pitch, multi-bay portal frame types were investigated, being simple in construction and practical in utilisation in the small industrial domain. These are the side supported portal frame and the centre supported portal frame. The side supported portal frame in Table 2 was analysed under the same loading conditions as for the preceding single bay portals. The larger roof area results in greater wind induced forces. In practice, the side bays thus contrived are typically utilized as post-production areas. Compartments of these side bays may also be well suited to providing office and ablution facilities.

In many practical industrial layouts, principally those in which smaller machinery (e.g. textile industry) is utilised, the portal clear span is not important, making it possible to introduce a centre support to the portal span. The centrally supported portal was again analysed under the same loading conditions as the preceding portals.

The results are summarised in Table 2. When strengthening of the basic portal lipped tube section is employed in locations of peak bending moments, the potential portal spans are further increased as is reflected in Table 3.

TABLE 3. Portal Spans in meters with Strapping at Indicated Locations

Lipped channel tube section			
Two channels	**strapped at eave peak BM**	**strapped at eave**	**strapped at hogging over supports**
100x50x20x2	8.2 (50x5)	moments uniform	moments uniform
125x50x20x2	9.4 (50x5)	9.1 (20x5)	9+6=15 (40x5)
150x50x20x2	11.0 (50x5)	10.7 (20x5)	10+6=16 (30x5)
175x50x20x2	12.4 (50x5)	11.9 (20x5)	11+6=17 (20x5)

COST IMPLICATIONS

The costing of a site specific industrial building structure is complex, being subordinate to a great variety of parameters independent of the structural layout, e.g. geographical placing with regard to availability of materials and labour, geotechnical conditions, site preparation, infrastructural layout, etc. The potential saving in cost in the establishment of the portal frame, based on the proposed alternative concept, may however be significant.

Various factors related to the alternative concept contribute to savings in cost, i.e. alternative site manufactured structure, use of standard commercial steel profiles, use of mainly unskilled labour, lower mass of material due to implementation of exoskeleton design approach, speed of erection, etc. In this regard, a typical small industrial building of 240 m^2 floor area was completed in South Africa during September 1995 for less than half the cost of a similar conventional structure.

It may be consequently be concluded that the proposed construction method, alternative to the conventional in Southern Africa for the industrial building sector, not only has the potential to create employment for the unskilled labour sector, but has the added potential of being more economical in the small industrial and related structural arenas.

PRACTICAL FEASIBILITY

Some experimental structures, employing the principles discussed in this paper, were constructed during 1995. Although most of the structures are small, the endeavour was to practically test the proposed alternative construction procedure. All the structures were built with the same team, comprising one skilled welder assisted by four unskilled labourers. The construction procedure not only worked well, but was in addition complemented by very fast erection times.

All the structural frame elements were cut with hand-held angle grinders and welded together on site. The IBR roof cladding material was positively fixed through the troughs of the profile by either 6.3 mm self-drilling, self-tapping screws or 4.8 mm rivets. Only cold-formed steel sections of 2 mm wall thickness were employed. None of the structures contain any bracing. Stability is provided by stiff frames and stressed skin diaphragm action by the cladding.

It may be concluded that the simplicity of practical details, concurrent with the ease of erection, established the practical feasibility of the proposed concept.

CONCLUSIONS

This paper covers a broad spectrum of features. The following conclusions may however be drawn:

- The proposed concept meets the demand of strategic economic policy by the establishment of more economical small to medium industrial and related type structures, complemented by the creation of employment for the unskilled labour sector.
- The versatility of the concept is indicated by the wide range of potential applications ranging from industrial type structures to low-cost domestic housing.
- Optimum use is made of materials by the exoskeleton design approach followed, whereby the cladding material is employed as an integral structural component through the principles of stressed skin diaphragm action, as well as the utilisation of the most appropriate footings for these lightweight portal structures.
- Use is made of only standard commercially available cold-formed steel profiles.

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