Oct 17th, 12:00 AM

Study of Innovative Built-up Cold-formed Beams

Gianmaria di Lorenzo

Raffaele Landolfo

Sixteenth International Specialty Conference on Cold-Formed Steel Structures
Orlando, Florida USA, October 17-18, 2002

Study of Innovative Built-Up Cold-Formed Beams

Gianmaria Di Lorenzo[1] and Raffaele Landolfo[2]

Abstract

In the present work innovative built-up cold-formed steel beams are presented. These are obtained by combining the pressing and cold-rolling forming techniques of steel sheets, along with the use of suitable connecting systems. Firstly, the beam shape features and the possible application fields, as well as the research project devoted to the assessment of their structural behaviour, are discussed. Then, experimental results concerning the characterization of both sheet material properties and connecting system performances are shown. In particular, the study of the sheet material is carried out by using an appropriate methodology of analysis, aiming at evaluating both mechanical and geometrical imperfections arising from the whole manufacturing process. At the same time, the mechanical behaviour of different connecting systems is investigated by means of several lap shear tests. The obtained results have provided useful design information and will be subsequently used to calibrate the numerical and theoretical models, addressing the prediction of the structural response of these innovative cold-formed beams.

Introduction

In the field of cold-formed steel structures, the high structural efficiency which can be achieved both optimizing the cross-sectional shape and using new materials, together with suitable connecting systems, are producing more and more innovative constructions, which can be globally defined as High-Tech Systems (Davies, 2000).

The growth of cold-formed steel structures started in the 1990's both in North America (Shuster, 1996) and Northern Europe (Lawson, 1996) construction markets. In fact, in such countries the cold-formed members, traditionally used as secondary beams (purlins and grits) in industrial buildings (Coskun, 1999), started being widely employed in residential constructions as well. In this application field, the light gauge cold-formed steel structures have proved to be a suitable alternative to the traditional constructive technologies based on timber, reinforced concrete and masonry. In fact, the main advantages of cold-formed systems concern both the structural performance (thanks to their high strength-to-weight ratio) and the technological aspects (better protection systems with respect to fire and superficial corrosion actions, more efficient manufacturing process, shorter construction times). Thus, the competitiveness of this technology is mainly based on the economical benefits coming from the remarkable saving of material, as

[1] PhD student in Structural Engineering, University of Chieti "G. d'Annunzio", Pescara, Italy.
[2] Full Professor in Structural Engineering, University of Chieti "G. d 'Annunzio", Pescara, Italy

well as the reduced construction time (Pedrazzi & Lozano, 1998). On the other hand, several studies and a considerable amount of research have been carried out aiming at checking the reliability of the cold-formed steel systems also from a structural point of view: when adequately designed, they may perform remarkably well, even in seismic areas, both in terms of strength and ductility. In order to attain such an ambitious goal, some typical limitations in the structural response of cold-formed members, mainly due to their high sensibility to local, distortional and/or coupled instability phenomena (Schafer & Pekoz, 1999), should be overcome. Some significant results have already been attained, such as the use of cold-formed structural systems in the construction of multi-story residential (Lawson & Ogden, 2001) and industrial buildings (Kurzawa et al., 1999), footbridges and provisional structures (Davies, 2000), as well as in retrofitting or superstructuring of preexisting buildings (Dubina et al., 2000).
The development of a new cold-formed constructive system generally starts from the preliminary idea of a new structural member. In this regard an emblematic example is the light-weight cold-formed beams recently investigated by Pedreschi (1999). Analogously, new built-up structural members, the so-called MLC beams, have been recently developed by an Italian Company (Ben Vautier SpA) in cooperation with the University of Chieti "G. D'Annunzio". The target is to obtain high performing members through the useful combination of different cold-forming techniques of sheet material together with the use of suitable connecting systems. Aiming at the structural assessment of MLC beams, a wide research program is ongoing at the University of Chieti. Within this project, the current paper provides a first contribution, mainly devoted to explaining aims and stages of the whole research program. At the same time, the first experimental results concerning the characterization of both the sheet material properties and the connecting system performances are reported and discussed.

The members

The MLC beams (design patent n. RM98A000598) belong to the built-up member typology. They are obtained by connecting two cold-formed shapes, through mechanical fasteners, located in correspondence of the web and of the flanges, where reinforcing plates are located as well (Fig. 1). These plates not only provide a connection between the cold-formed parts, but also improve the structural performance of the whole beam, so allowing the possibility of using different thickness and/or material.
Shape and position of bends and folded grooves are designed to optimize the bearing capacity of the proposed built-up beams. The aim is to reduce the effects of local buckling phenomena in both the flange and web elements, leading to a very efficient structural member. The flanges are stiffened by edge and intermediate stiffeners (made of folds and folded grooves, respectively), while the web stiffeners are made of two semi-cylindrical curved grooves which, once the beam is assembled, form a sort of truss system, whose braces have a hollow cross-section.
Lighter version of the MLC beam can be obtained by introducing lightening holes in the web, aiming at allowing the technological plant crossing as well. In this regard Figure 2 shows some examples of proposed beams containing openings.

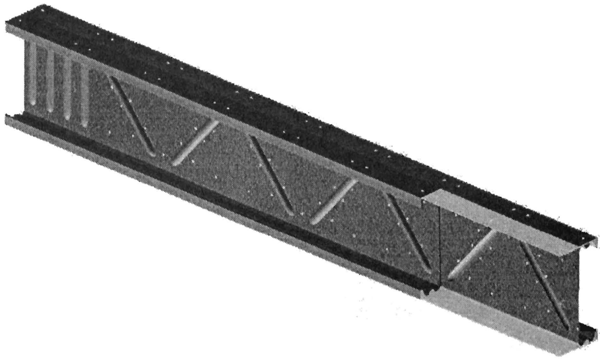


Figure 1: The built-up cold-formed steel beam

By combining successfully all the above mentioned typological aspects characterizing the MLC beams (reinforcing plates, stiffening devices and web holes), it is possible to obtain a new generation of cold-formed members, which can be suitably used in several application fields. Of course, in order to be on this target, it is necessary to set-up an appropriate design procedure able to individuate, for each possible application field, the best combination of both structural and technological beam features.

With regard to the first aspect, it is worth underlining that the structural performance of the proposed beams can be improved by modifying the properties of both the sheet material and the other beam components. In fact, the two halves, usually in mild steel, may be made, for special applications, of high-strength steels, in accordance with a general trend in increasing the use of such sort of materials in cold-formed structures (Rogers *et al.*, 2001). At the same time, the reinforcing plates – usually of steel – may be also made of different materials (aluminum, composite materials and timber). Obviously, the outcoming structural performance of the MLC beam should be, in each case, guaranteed by effective and innovative connecting systems (bi-component and mono-component blind rivets, self-piercing rivets and press-joints), able to provide high structural responses together with a remarkable workability.

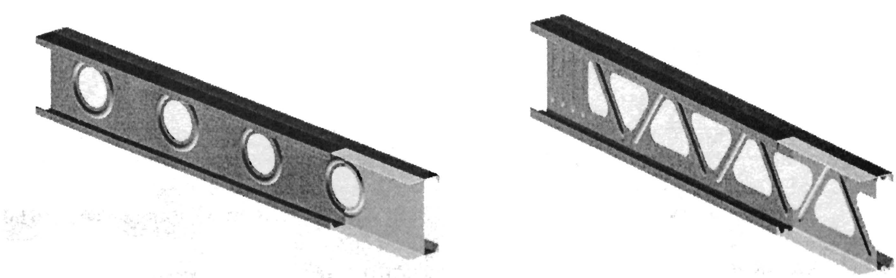


Fig. 2a) Fig. 2b)

Figure 2: Examples of built-up beams with open web

Consequently, the potential application fields of the proposed beams appear to be manifold. Obviously, the key aspect is the competitiveness of MLC beams respect to equivalent hot-rolling members. From this point of view, the final cost is undoubtedly the crucial parameter and it must be considered as an additional target in the relevant design procedures.

The research project

The complexity of the beams under examination has required the development of an appropriate research project aiming at the assessment of their structural behaviour. The whole study is on the following main directives:

1. Experimental investigations devoted to evaluate strength and ductility of both beam and its components under different loading conditions.
2. Theoretical and numerical analyses aiming at simulating the whole beam response starting the components modeling.

With regard to the first directive, the design assisted by test methodology will be adopted, in accordance with the provisions of the main European codes on cold-formed members (ENV 1993-1-3, 1996 and ECCS n.49, 1987). As far as the theoretical and numerical aspects are concerned, deterministic (finite strips and/or nonlinear finite elements), not deterministic (soft computing) and mixed methodologies will be used.

Thus, the results achieved through the experimental tests will be used both for design purposes and for calibrating the theoretical and numerical models.

The whole research activity has been subdivided in the following operative steps:

- *Step 1*: Preliminary study (study of the relevant "state of the art" and critical examination of the specific international design codes);
- *Step 2*: Characterization of the beam components (selection of the sheet material and of the connecting systems, optimization of both cross-section shape and stiffening devices);
- *Step 3*: Experimental tests on single components (tensile tests on base material before and after cold-forming process, lap shear tests on selected connecting systems);
- *Step 4*: Study of the assembly and competitiveness problems (design of the mechanical fasteners with regard to current connections and end joints);
- *Step 5*: Experimental tests on beams (selection of different beam specimens, full-scale tests on the selected specimens under different load conditions, elaboration and critical interpretation of test results);
- *Step 6*: Theoretical and numerical analyses by using computational models previously calibrate;
- Step 7: Design of a specific MLC beams in accordance with different application fields.

The research is in progress and has reached step 4. The first two stages have allowed the preliminary definition of the beam shape, which shall be checked through the subsequent steps. Besides, a possible sheet material (steel S235JR) as well as some connecting systems (mono-components and bi-component bind rivets, self-piercing rivets and press-joints) have been selected. A briefly overview on the main obtained result is presented in the following. More detailed information about such aspects are reported in the relevant papers (Landolfo & Di Lorenzo, 2001; Di Lorenzo & Landolfo, 2002; Di Lorenzo & Landolfo, 2003).

The characterization of the beam material

The characterization of the material, e.g. the definition of its suitable behavioural model, is undoubtedly one of the most important aspects for studying the structural response of a member. With reference to MLC beams, the complete and correct identification of the "*material mechanical model*" has required the set-up of an appropriate methodology of analysis aiming at the assessment of all the imperfections arising from the whole manufacturing process. In particular, such a methodology is based on the separated evaluation of the effects on the material produced by rolling first (on the base sheet), then by cold forming (on the final shape).
As far as the first aspect is concerned, a relevant experimental investigation (Landolfo & Di Lorenzo 2001; Di Lorenzo & Landolfo, 2003) has been preformed with reference to a S235JR steel sheet with nominal thickness equal to 2.00 mm [0.079 in]. The study has focused on the evaluation of both mechanical and geometrical imperfections induced by the rolling process on the sheet material, owing to the interaction among rolls and flat sheets in the plastic and thermoplastic fields.
With regard to mechanical imperfections, the tensile tests carried out on specimens taken out directly from the sheet under investigation (Fig. 3) have shown that they basically consist of the variation of the main material properties along the sheet. Such imperfections are more remarkable along the cross direction of the sheet, where a parabolic variation of the material strength parameters has been noticed. Figures 4a and 4b show the tensile test results in terms of yield (f_y) and tensile (f_u) strength, respectively. The data, for the sake of comparison, are normalized through the nominal strength values, equal to $f_{y,b}$=*235* N/mm^2 [34.1 ksi] and $f_{u,n}$=*360* N/mm^2 [52.2 ksi], respectively. The obtained results well emphasize that such a variation is particularly considerable for f_y, with a variation of about 12% between edge and middle values. On the contrary, in case of f_u, the variation is equal to 4% only.

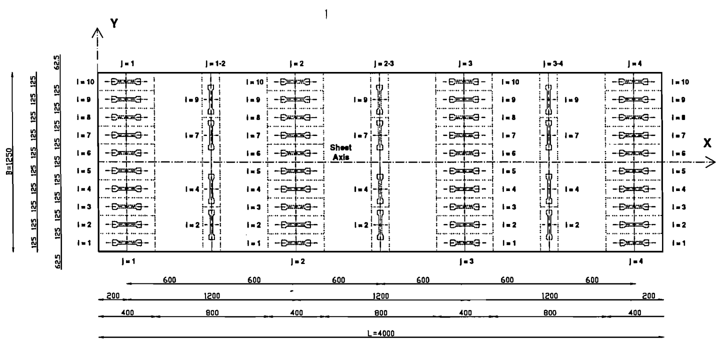


Figure 3: Arrangement of the tensile test specimens on steel sheet S325JR

The rolling process introduces in the sheet material a light anisotropy behaviour as well. This has been well evidenced by the tensile tests carried out on the specimens taken out along the cross direction of the sheet. However, such an effect appears to be quite negligible, being the yield strength measured along the transverse direction only a few percent higher than the one measured along the longitudinal direction.

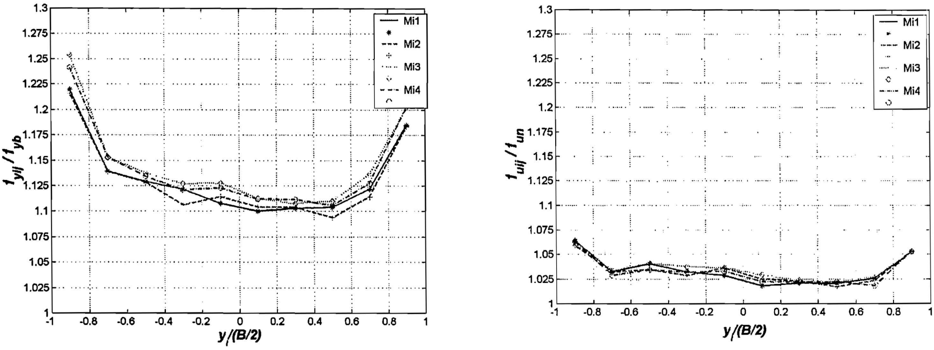


Fig. 4a) Yield strength

Fig. 4b) Tensile strength

Figure 4: Experimental trend of the sheet material properties

As far as the geometric imperfections due to rolling process are concerned, the most important one, from a structural point of view, is the variable thickness distribution. In fact, the roll-plate interaction leads to a sheet cross-section characterized by higher values of the thickness in the middle rather than along the edges. With reference to the steel sheet under investigation, Figure 5 shows, in normalized way, the deviation of the measured thickness in comparison with the nominal value. The maximum scatter (±1%) is proved to be negligible, it being largely below the allowable product tolerance (±7%) provided by EN10051 (2000).

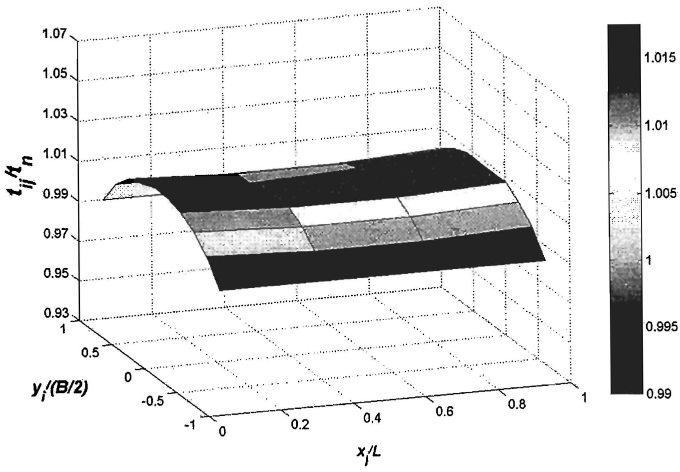


Figure 5: Experimental trend of the sheet thickness

The Influence of cold work on material mechanical properties

As it is well known, the cold-working process of steel sheets, which is necessary for the manufacture of cold-formed members, is characterized by the plastic deformations of the base material performed through cold roll forming and/or die forming. Therefore, further mechanical and geometrical material imperfections arise, in addition to the ones induced by the previous rolling process, next to the folded zones.

The mechanical imperfections basically consist of the variable distribution of the mechanical properties (mechanical heterogeneity) and by residual stress, both of them located next to the folded zones. The mechanical heterogeneity is due to both strain hardening and strain aging effects (Yu, 2000), generally determining both a strength increase and a ductility reduction.

The study of the material alterations produced by cold working is particularly interesting for the MLC beams. Such members, in fact, are characterized by a complex cross-section shape, having the folds with bend angle ranging from 0° to 180 °.

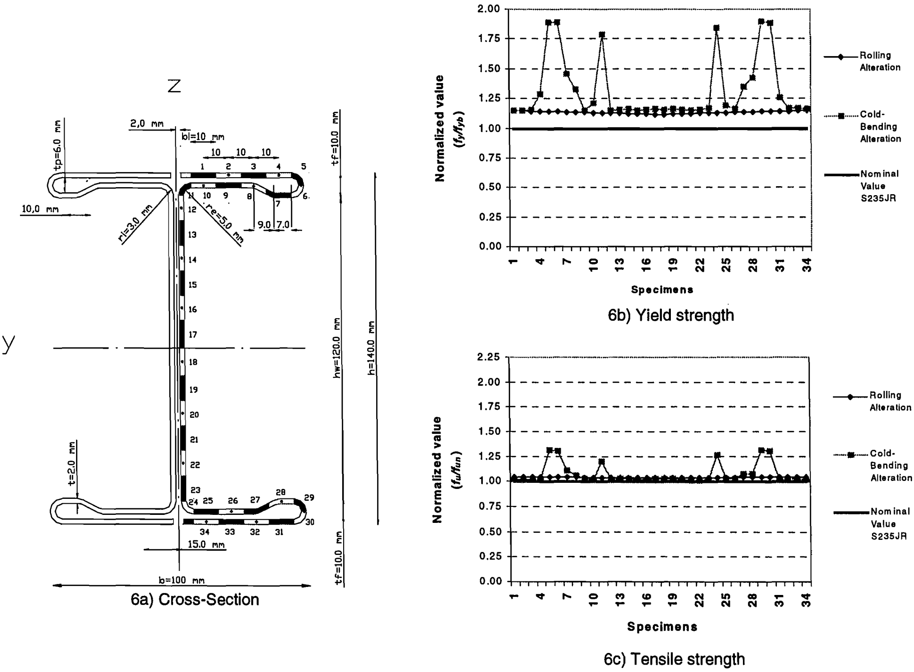


Figure 6: Effects of cold work on material properties

In order to evaluate the influence of cold work on a first type of MLC beam, a specific experimental study has been developed (Di Lorenzo & Landolfo, 2003). In particular, through tensile tests carried out on specimens taken out directly from the examined beam (Figure 6a), it has been evidenced that the yield strength is the material property mostly influenced by the cold working process. In fact, if compared with the relevant nominal value ($f_{y,b}$=235 N/mm^2 [34.1 ksi]), it is possible to observe, near the folds, a rise in f_y varying between 80 and 90%. This difference can be reduced to 60 ÷ 70% if the actual values of yield strength, by including also the rolling process effects, are considered (Fig. 6b). On the contrary, the variation in terms of tensile strength has proved to be lower, with variations from 20 to 30% about the relevant nominal value (Fig. 6c). As far as the geometrical imperfections are concerned, they mainly consist of the necking occurring in the fold zones. In fact, a higher level of plastic deformation produces in the base sheet a reduction of the thickness (t), which is negligible if a limitation on the bend radius (r) is respected (r/t>1,5). In the examined case, a thickness reduction of about 0.5% has been found: this was expected, since the cross-section shape fulfils the requirements concerning the internal radius.

The connecting systems

The choice of a useful connection technology is generally a key aspect to design cold-formed structures. This problem particularly concerns the MLC beams, whose structural behaviour is strongly influenced by the connecting systems as well. For this reason, the relevant experimental activity, mainly devoted to individuate the best connecting solution both from a technological and a structural point of view, has been performed (Di Lorenzo & Landolfo, 2002).
As first step, some fasteners produced by the Avdel-Textron Fastening System have been selected (see Tab. 1). All of them belong to the category of the innovative connecting systems and are characterized by a good compromise between high performance and workability.

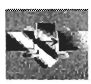
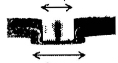
Name	AVDELOK 2611	HEMLOK 2221	FASTRIV FAS11	AVICLINCH
Manufacturer	Avdel Textron	Avdel Textron	Avdel Textron	Avdel Textron
Fastener type	Bi-component blind rivet	Mono-component blind rivet	Self-piercing rivet	Circular press-joint
Material	High-strength low-alloy steel (galvanized 7μ)	Galvanized high-strength low-alloy steel	High-strength low-alloy steel (galvanized 3μ)	Sheet material
Diameter (mm)	d_b=6.5	d_b=6.5	d_b=4.8	d_p=5.00 *(punch diameter)* d_d=6.50 *(die diameter)*
Nominal shear strength $F_{v,Rn}$ (KN)	14,73	17,00	-	-
Cross section				

Table 1: The selected fasteners

The mechanical behaviour of each selected connecting system has been investigated by lap shear tests carried out on specimens involving two sheets (*asymmetrical specimens*). Only for the blind rivets, the tests have also concerned specimens involving three sheets (*symmetrical specimens*) (Fig. 7).
The critical analysis of the test results has emphasized, at first, that the response of the asymmetrical specimens is strongly influenced by the existing eccentricity between the flat

sheets. The most penalized mechanical property is the ductility that, in case of the mono-component blind rivets, has proved to be 5 times lower than the one of the corresponding symmetrical joints. Of course, also the strength reduction due to such effect is significant as well, with variations of about 50%.

For the sake of comparison, the average shear responses of all the selected asymmetrical specimens are depicted in Figure 8 [1 KN = 224.8 lbf and 1 mm = 0.039 in]. The completely different response of the bi-component blind rivets was due to the particular failure mode, which did not involve the shearing of the fasteners. In this way, the bi-component blind rivets showed the highest performances both in terms of strength and ductility. In particular, as far as the ductility is concerned, the slips at failure experienced by such kind of fastener, has proved to be 3 times grater than the one occurred for mono-component blind rivets and self-piercing rivets, and 7 times greater than specimens jointed by circular press-joint. Relatively to the shear strength, the differences in performance appear to be less evident than ductility but, however, of one order of magnitude greater than clinches.

As regards the design aspects, the obtained results clearly suggest the use of bi-component blind rivets where ductility restoring connections are required (for instance for flange connections). On the contrary, where such requirements are not strictly necessary (e.g. web connections) the mono-component bind rivets and self-piercing rivets can be also adopted.

In addition, the experimental response of the selected connecting systems has been used to set up, for each one of them, simple behavioural models which will be used for further numerical simulations of the whole beams.

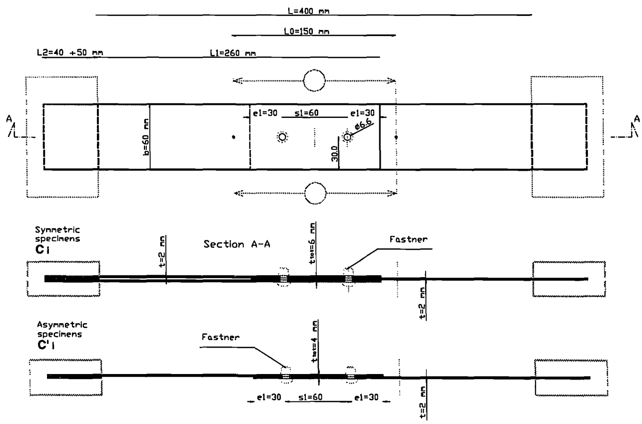


Figure 7: Specimens for lap shear tests

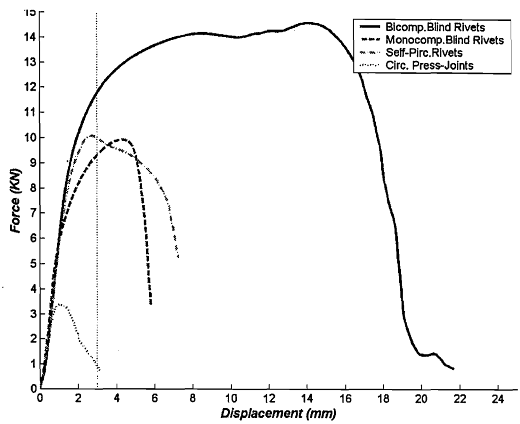


Figure 8: Average experimental responses of lap shear tests

Conclusions and further developments

In the current paper innovative cold-formed built-up steel beams have been presented. They are obtained through the useful combination of pressing and cold rolling forming techniques of steel sheets, together with the employment of suitable connecting systems.

On such members a wide research project developed and coordinated by the University of Chieti in cooperation with the Italian Company Ben Vautier Spa is in progress.

Together with the beam features, the application fields and the research program purposes, some experimental activities aiming at the assessment of the structural behaviour of the main beam components (material and connecting systems) have been described.

The characterization of the base material has been performed by using an appropriate methodology of analysis able to assess all the imperfections arising from the whole manufacturing process. In particular, by means of the relevant tensile tests, it has been pointed out that the rolling process produces in the material sheet both geometrical and mechanical imperfections. The former consist of a variable thickness distribution, while the latter, much more important from a structural point of view, mainly consists of the variation along the sheet cross direction of the material strength parameters. In particular, this variation is quite significant for the yield strength, which varies of about 12% between the edge and the middle of the sheet.

Further mechanical and geometrical imperfections are caused by the subsequent cold forming process. In particular, small thickness reductions around folded zones have been pointed out. On the contrary, the yield strength has proved to be, also in this case, the mechanical parameter most significantly influenced by the process of workmanship, with variations of about 60% (by including also the rolling process effects) respect to the relevant nominal value of yield strength.

The main experimental activities addressed to the choice of the best connecting system have been shown as well. With regard to this aspect, the mechanical response of several fasteners has been

investigated by lap shear tests carried out on both specimens with two and three sheets respectively.
The outcomes seem to suggest the use of bi-component blind rivets where ductility-restoring connections are required (flange connections), while the mono-component blind rivets and self-piercing rivets could be properly used in the web.
All the aforementioned activities concerning the MLC beam components have provided useful design information. In addition, the obtained results will be used to calibrate the theoretical and numerical models aiming at simulating the structural response of the whole beams.

Acknowledgments

The authors would like to acknowledge Ben Vautier Spa for the initiation and support of this research project.

References

CEN EN 10051 (2000). Continuously hot-rolled uncoated plate, sheet and strip of non-alloy and alloy steels-Tolerance on dimension and shape.

CEN ENV 1993-1-3 (1996). Eurocode 3: Design of steel structures – Part 1-3: General rules - Supplementary rules for cold formed thin gauge members and sheeting.

Coskun H. (1999). Design consideration for light gauge steel profiles in building construction. 4th International Conference on Steel and Aluminum Structures - ICSAS'99, Helsinki.

Davies J.M. (2000). Recent research advances in cold-formed steel structures, Journal of Constructional Steel Research, Vol. 55.

Dubina D., Georgescu M., Ungureanu V., Dinu F. (2000). Innovative cold-formed steel structures for one storey penthouse superstructure of Datatim-Alcatel industrial building, Proc. of 9th Int. Conf. on the Metallic Structures, Timisoara.

Di Lorenzo G. and Landolfo R. (2002). Comparative study of new connecting systems for cold-formed structures. Proc. of the 3rd European Conference on Steel Structures, Coimbra.

Di Lorenzo G. and Landolfo R. (2003). On the characterization of material properties for cold-formed members. Proc. of International Conference on Advances in structures (ASSCCA'03). Sydney (submitted paper).

ECCS n.49 (1987). European Recommendations for the design of light gauge steel members, (First edition).

Kurzawa Z., Rzeszut K. Boruszak A., Murkowski W. (1999). New structural solution of light-weight steel frame system, based on the sigma profiles. 4th International Conference on Steel and Aluminum Structures - ICSAS'99, Helsinki.

Landolfo R., Di Lorenzo G. (2001). Una nuova generazione di membrature leggere formate a freddo. XVIII Congresso CTA, Vol.2, Venice (in Italian).

Landolfo R., Di Lorenzo G. and Fiorino R. (2002). Attualità e prospettive dei sistemi costruttivi cold-formed, Costruzioni Metalliche, n.1 (in Italian).

Lawson R.M. (1996). Residential applications of light steel frames in the UK and Continental Europe. 5th International Colloquium Structural Stability Research Concilium SSRC, Chicago.

Lawson R.M., Ogden R. G. (2001). Recent developments in the light steel housing in the UK, 9th North Steel Conference Steel Construction Institute. Helsinki

Moen L.A., Langseth M., Hopperstad O.S. (1998). Elastoplastic buckling of anisotropic aluminum plate elements, Journal of Structural Engineering, ASCE, 124 (6).

Pedrazzi F.L.M., Lozzano S. (1998). The development of light weight steel structures for housing in Argentina, Journal of Constructional Steel Research, Vol. 46 1-3.

Pedreschi R. F., (1999). Design and development of a cold-formed lightweight steel beam. 4th International Conference on Steel and Aluminum Structures - ICSAS'99, Helsinki.

Rogers C.A., Yang D., Hancock G.J. (2001). Stability and ductility of thin-walled high strength G550 steel members and connections, Proc. of 3rd International Conference on Thin-Walled Structures, Cracow.

Schafer B. W., Pekoz T., (1999). Local and distortional buckling of cold-formed steel members with edge stiffened flanges, 4th International Conference on Steel and Aluminum Structures - ICSAS'99, Helsinki.

Schuster R.M. (1996). Residential applications of cold-formed steel members in North America, 5th International Colloquium Structural Stability Research Concilium SSRC, Chicago.

Yu W.W., 2000, Cold Formed Design (3rd Edition), John Wiley & Sons.