Automated Production of Generic-Form Reinforced Concrete Structures through Use of an Improved Progressive Strength Construction Method

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Abstract

This paper relates to the development of a method for the total automation and site robotisation of the concrete frame production process on real world, non-standardised, commercial building structures. The proposed method uses currently available technology and is an improvement on the highly successful Progressive Strength System developed in Australia in the 1970's to produce many major office buildings and other structures. This paper reviews the PS system from a technical and economic point of view and then indicates how the original production process can be improved using modern automation concepts to produce a totally automated site production process that is undoubtedly cheaper, faster and safer in real terms than the current orthodox production process.

1. Introduction

Over the last few decades, much work has been done around the world relative to development of advanced production systems for the site-manufacture of buildings. Whilst considerable success has been achieved in building construction endeavours in Japan, most of the work done has little relevance to the rest of the world. This is because most of the automated production work done in Japan relates to the construction of highly shape-standardised, steel-framed office structures in heavy earthquake zones. Normally, however, very different conditions apply in the rest of the world where reinforced concrete construction systems of quite arbitrary shape tend to prevail and where serious earthquakes do not occur. The focus of this paper thus is not on heavy-framed steel structures but rather on the automated manufacture of shape-unconstrained (parametric-form) reinforced concrete structures where standardisation and normal industrialised manufacturing systems typically cannot be applied.

In this connection, it is noted that automated production of reinforced concrete structures is a significantly different (and more difficult) problem to that of the automated assembly of steel structures. The difference arises firstly because of a lack of a steel skeleton for use in heavy load bearing and materials handling applications during construction and secondly because of the general messiness of the process of reinforced concrete structure production. As a consequence automation of reinforced-concrete structures production is much harder than for steel framed structures production.

2. Some alternative philosophical approaches to the concrete building automation process

For the full automation of site concrete construction activity, it seems that there are two basic alternatives; either (i) automate the conventional (historical) concrete construction processes [1] or (ii) re-engineer the existing processes, streamline them and make them more suited to mechanised processes and then apply automation technology. Of these two, the second is considered most likely to achieve success in the near term and hence in the one discussed in this paper.

3. Process simplification and falsework free construction methods

The idea of 'Progressive Strength' as a method for re-engineering the standard reinforced concrete building construction process emerged from the observation that in the traditional method of building construction two complete and very expensive structures are built. The first is a temporary falsework structure that is built up, true to detail, and then demolished. The second is the 'true' structure and the only one that the client values. The 'virtual building' is required only as type of construction accessory. From this perception, a basic question arises "*can we build only one structure since it seems not logical to have to build a hugely expensive falsework structure to support the real structure?*" Alternately put, "*is it possible to build only the real structure and eliminate the need to build and demolish a very expensive virtual structure?*". A one-structure-only strategy would seem to be logically possible since it is clear that in steel-framed buildings only one structure is indeed built. Hence, one can conclude that there is no *logical* need for a virtual structure. The key stratagem seems to be to use the structure as it's own scaffold.

If only one structure can built then large cost saving can potentially be made. Formwork and falsework, for instance, typically comprises around 60% of the final cost of a reinforced concrete element. Also, if falsework-free construction can be achieved then prop-free underside access to suspended slabs can be achieved for mobile machines plus there is no reverse materials flow required for the removal of used falsework materials.

From an automated building systems point of view, the need to build and then destroy and remove a complex and bulky virtual structure is much to be avoided since these processes tends to create many problems of their own. From a material handling point of view, for example, much of the virtual structure gets 'topologically-trapped' in the real structure and much of the problem of formwork and falsework handling is in trying to move it about and around parts of the permanent structure. Alternately, falsework components have often to be broken down into sizes sufficiently small to be able to pass through small apertures in the real structure. Even worse, sometimes parts of the virtual structure have to be passed though areas that are filled with other parts of the virtual structure. Yet again, the virtual structure requires a full reverse material handling operation wherein material have to be both shipped into the site and removed from it after the job. Removal of all these material at the end of the job extends the duration of the job and places much demand on the material handling systems that might be required on the job. Also, crane-hook availability is often the defining factor in the time to complete a major building. Handling and re-handling hundreds of tonnes of virtual structure is thus an obvious logical impediment to the fast completion of structures that are cranage limited.

4. A review of the original 'Progressive Strength' building system

Progressive Strength (PS) was a 'first-generation', process re-engineered, falsework-free, concrete frame production method developed and used in Sydney in the 1970's by one of Australia's top property development and construction firms. The system was developed by a team of production engineers using advanced manufacturing concepts and philosophies and was used in the construction of approximately 20 major high and medium rise buildings in Oceania. The system was also employed to build the 68 level MLC building in downtown Sydney [2]. At the time of its construction the MLC building was the world's tallest reinforced concrete office structure (fig 1). The project was hailed as a major engineering achievement at the time and received a number of engineering excellence awards. The PS system was a considerable commercial and technical success at the time and was subject to intense economic scrutiny by cost-planners, estimators, project managers and research and development engineers as to its virtues as compared to more orthodox construction methods.

Figure 1 - The 68 level MLC centre in Sydney

A review of the philosophy of PS construction method is given in Appendix and in Refs [3-4]. In brief, the PS system is a 'total-building' system that was conceived of from the bottom up. It is an hard-automation based systems-building production process wherein the normal reinforcement contained in an reinforced structure is redesigned and welded together to form 'internal falsework' members. These internal falsework members were used to support a, three dimensionally staged, concrete pouring process that allowed the structure to be constructed without overloading any sections of the internal falsework. No falsework or concrete support props, in the traditional external sense, were employed. In the PS method, large amounts of highly automated off-site prefabrication were used to produce the internal falsework items. Further, the whole building was designed to be put together using low volumes of non-highly skilled site labour using assembly line and simple pick and place erection techniques.

In implementing the core PS idea, the principal difficulty lay in devising a structural system that could be broken up into a stackable modular internal 'armature' system without incurring an excessive supplemental reinforcement premium. In the PS system - as developed by Civil and Civil Pty Ltd in Australia - a 'kit-building' system was developed to produce a 1 way ribbed floor structural system based on welded reinforcement based armature modules capable of supporting formwork panels. There were no underside props. The system utilised the following small set of components:-

- Precast concrete and removable load bearing column form members.
- Prefabricated primary girders as modular armature units.
- Clip-on steel framed plywood panels to the primary girders.
- Secondary open web joist trusses as drop into place modular armature units. These trusses were mass produced under large volume factory conditions
- Timber runners with clips to the underside of the joists
- U shaped coffer or trough forms that ran and spanned between the joists and rested with their lower lips on the timber runners. These polypropylene coffer panels were injection moulded mass produced items.

All the above items were relatively low tolerance components with locating-pin or drop-in type connectors. Low tolerances and loose connections are adequate since all the pieces are bound together at later stage by the cast-in place concrete.

Construction involved erection of a minimal set of these elements and pouring concrete progressively in various infill pours (on a three dimensional pattern). Stripping of formwork occurred from the underside of the deck slab by a process of removing the timber runners and stripping off the plastic U-shaped coffer elements. The stripping process was assisted by a compressed air blow-off tool.

After manual inspection and cleaning the small sized coffer forms were taken by conveyor and then passed up through a small aperture in the finished floor to the next deck. The amount of between-floor material handling work was minimal as a consequence of all pieces of formwork being constituted into small repetition units. All major in-bound material handling operation were handled from above by a site crane. Figures 2 and 3 show the system in use.

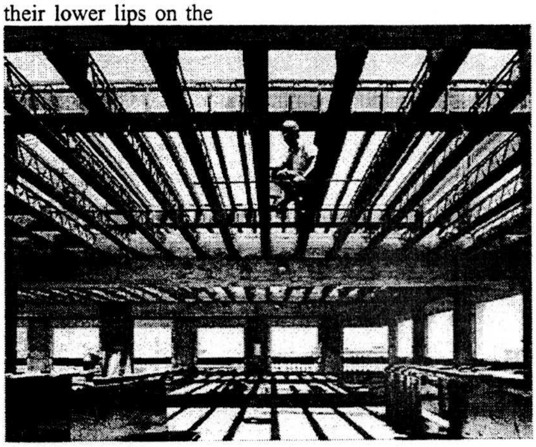

Fig 2 - A general view of a high rise office structure being constructed by the PS method

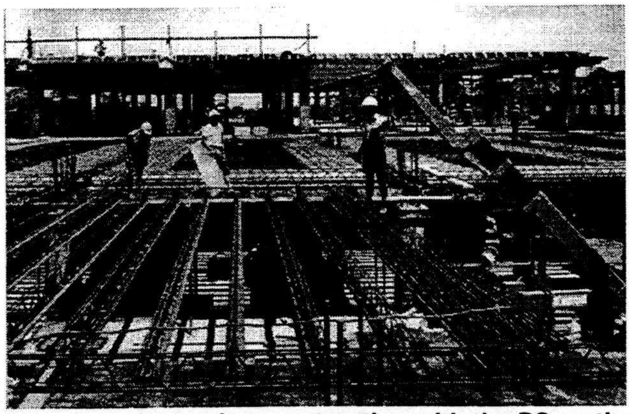

Fig 3 - A large shopping-centre complex under construction with the PS method

In economic terms the PS method was absolutely cheaper than normal construction on buildings with high typicality. On structures with low volumes of typical floor sections the system was perhaps 10% more expensive. The PS construction system was absolutely cheaper in situations with high floor to floor heights or in situations were the way beneath had to be kept clear, as for instance, when building over rail tracks. The original PS system provided some major construction and production engineering benefits in that standardisation of structure was accomplished, site operations were grossly simplified and almost all of the traditional reinforcing steel placing and fixing operations was removed off-site to automated production facilities. Falsework systems were eliminated and there was no propping of floors. This prop-free aspect of things has a considerable benefit in that it allowed free access for mobile construction and material handling equipment and provided a clean and uncluttered environment. The method also eliminated all manhandling of traditional falsework and propping systems and simplified materials handling flows.

Specifically the original PS system provided:

* An uncluttered prop free site.
* A 50% reduction of on-site labour.
* Minimal requirement for specialised manual or trade skills
* Much quicker that conventional methods once underway
* Assembly line production processes.
* Site assembly largely based on pick and place simple drop into place operations.
* Flexibility to accommodate suspended ceilings, electricals and mechanical services operations.
* High in-built levels of quality control.

Whilst having a number of positive aspects the PS system also had some negative features.

* In use, the system came to be recognised by users as being quite cumbersome as it required a large centralised, hard-automation, truss manufacturing plant to support a, geographically diverse, number of projects. Being tied to a single production plant plus the need to truck components large distances around Australia came increasingly to be seen as a limiting factor both in time and cost but also in flexibility. Further, the need for a million dollar dedicated central manufacturing plant limited flexibility and the problems of matching of supply to demand under the vagaries of the building industry meant that senior management were loath to make large dedicated investment without solid prospect of a solid return. This limited the application of the original PS system as often projects became limited by central plant production capacity.
* The primary-girder armature modules were, to a significant degree, low volume 'specials' that could not be readily automated with the technology of the day. This made these components expensive to make and expensive to transport since they could not realistically be made on-site to demand.
* Also, one of the factors that tended to work against the PS system from a worker satisfaction point of view was the need to pick and place a large number of small components on a boring and repetitive basis. *{This is what modern robots are typically very good at but construction labourers dislike this kind of high repetition work. The conventional wisdom in labour based-construction systems is that lots of little components are to be avoided and the economies of scale are obtained from "ganging together" pieces into large assembles than can be handled by big machines. Using small machines to automate very tedious field processes is the opposite of the traditional constructor's philosophy. Ultimately however, adopting the obverse of the conventional wisdom and changing the traditional mind-set may be the key to economical introduction of site robotics and radical process re-engineering. Likewise, placing and fixing loose reinforcing bars is a very difficult process to automate in the field. The prefabrication of reinforcement into manufactured assemblies though totally obviates this difficulty.]*
* By reason of the staged construction process, in the PS method concreting operations become more fragmented and potentially less economical in term of achievement of the economies of scale that are typical of concrete work. Small concrete pours cannot be done economically if teams have to be mobilised to site and then only utilised for an hour or so.
* In the PS method the whole of the building construction process is designed as a totally integrated system which typically must be carefully staged in space and time and typically requires development of a three dimensional system of site operations based around a production-train notion. Planning of multiple, moving work face, operations in 3 dimensions is more difficult for site teams unaided by computer visualisation systems and hence was considered a negative feature by management teams of the day.
* Quite long lead times were required on the manufacture of components and this limited project management's flexibility.
* The structure has to be designed at the outset to be built using this method.
* The construction method tend not to suit standard trade based contract packages and outsourcing techniques.

5. Progressive strength revisited in the light of new manufacturing engineering technology

Since the 1970's there have been huge advances in production engineering and manufacturing engineering technology. For example, flexible automation and robotic automation ideas have been introduced. Computed assisted design (CAD) and computer assisted manufacture (CAM) technologies have been developed and many advanced sensor based quality control systems developed. Further, computer-integrated manufacture (CIM) ideas have been developed and successfully trialed world-wide. Collectively these new technologies have delivered great productivity improvements in manufacturing - especially as they apply to low volume manufactured products.

It is the argument of this paper that - everything else being held constant - application of these new technologies to the original 1970's PS system would have shown substantial economic benefit. The new technologies would have had the effect of lowering the cost structures of the PS method vis-à-vis the normal and making it in almost all cases more economical than the traditional methods - rather than only being clearly superior on large volume production runs.

It is well recognised, also, that flexible automation procedures reduces the cost of small volume component production as compared to jobbing practices. These procedures also reduce the capital outlay for getting into cost automated manufacture. Further, software driven machines allow for the introduction of individual unit variation - such as camber in trusses or variation in location spigots . Flexible automation allows bespoke units to be produced at near mass production prices.

Flexible manufacturing processes could have been used to great advantage in reducing the cost of the original PS construction system. Thus, for example, experience over the 20 or so projects carried out under the original 70's PS system indicated but the ribbed slab manufacturing processes were efficient and economical but that the primary beams were high cost items. Flexible automation ideas could have allowed for the more economical production of these primary beams. Likewise, flexibility could be introduced into the ribbed slab section by having software controlled manufacturing machines which could have allowed for length and depth variation as well as camber control. Further, slab reinforcement cages could have been produced in space frame form and not just in planar truss form.

A primary problem with the economic implementation of the PS system in the late 1970's was the need to set up a costly, centralised hard-automation based, open web joist production plant and the need to transport low load-density truss items long distances to the work site. The hard automation technology available at the time not only required a large cost outlay for specialised custom made welding lines but to a large extend required that all truss lengths and sizes be fixed in the interest of hardware invariant production equipment. In the system that was implemented in the 70's this meant that all structural bays had to be exactly a fixed length (normally set at 7.3 metres). Any across unit deviation from this dimension incurred a large cost- and time premium.

Another problem intrinsic in the original PS system was that the primary beams were typically in the form of quite heavy boxed space members rather than planar trusses and were hence hard to manufacture except by manual means. The members were low volume 'specials' and had to be manufactured individually.

With the coming of flexible automation ideas and high performance welding robots however these limitations need no longer apply and designers can have much greater flexibility in layout and special area treatments. Low volume, mass production of open web joists from standard stock by the methods of flexible automation are now possible and any and all truss sizes and web geometries can be produced without losing the site labour benefits of prefabrication and the cost and time economies of factory-type automation. With the availability of mass produced high performance welding robots (some 1 million of which are in use around the world) costs of welders are now low enough to make at-site fabrication of girders and trusses technically feasible. At-site production could reduce dramatically the cost of armature element cartage and truck transport and just-in-time production techniques can be applied. In addition, because flexible automation is used and the robots can be reprogrammed, the same technology can be used on many jobs and the costs of the robot systems amortised across many operations [10]. Alternately, because orthodox form welding robots are employed in the manufacture and prefabrication of normal steelwork such machines may either be leased or else local welding robot operators could operate as sub-contractors. Also, with the availability of induction and other forms of programmable bar bending equipment, joist webs can be continuously and accurately produced on demand and directly from CAD program.

Still again, there are some features of the original PS system that are quite easy to overcome nowadays through modern automation and design technology. Thus:

* One of the problems experienced by project architects and site managers was a feeling that the whole project was 'tied-to-typicality'. Any change from the standard layout caused difficulty and slowed the project. A regular comment from users was that the system was excellent on typical floors

but was not good on non-typical floors where, in truth, the orthodox methods were better and were in actuality generally used. Thus on a 'real' project PS and non-PS tended to be in use simultaneously - to the detriment of both.

* Because the system was difficult to adapt to non-typical floors, start-up effects using the PS system were always quite large with crews having to learn and get used to the assembly process under non-typical conditions. Nowadays, non-typicality can be allowed for in CAD design and crews can be trained with advanced visualisation technology [11]. By such means the break-even point of PS versus orthodox propped formwork construction can be much improved.
* In order to totally remove the occasional need to prop the primary beams, it is now possible to lessen construction and gravity loads by non-contact construction methods. With modern programmable construction equipment it is possible to remove men from the deck and generally manage construction loads by controlled deposition of concrete through programmable boom-pumps or automated shotcrete apparatus.
* In order to remove the need for 1 million dollar customised production plants, local industry flexible automation plants can be nowadays be invoked to produce elements very cheaply and effectively without large capital outlays. Also, the use of modern transportable robotic welding equipment and on site CAD controlled induction pipework bending systems can make activities such as the construction of low-volume custom made space frames quite economical and highly time efficient.
* One of the problems experienced with PS was long lead-times associated with more detailed design practices and with production timings on the prefabrication systems. With modern computer-aided-design and computer assisted manufacturing technology technologies and with current quick turn around flexible manufacturing systems, lead-time problems need not be such as worry.
* One of the somewhat unnoticed problems experienced in the PS system was the loss of economic potential though the need to mobilise teams of men and pour small volumes of concrete into members distributed in three dimensions. With modern programmable boom pumps [1] and CAD control however the [3-D] small volume procedure need no longer suffer from poor economics as compared to [2-D] large volume construction.

From all the above, one can conclude that even though PS was a technically good and fully commercially viable system in the 70's, it would have been a much better superior system if it had had the advantages of 1990's manufacturing technology. This would be the case even if no further innovations (such as will now be proposed) had been introduced.

6. Development of an economically much improved PS construction system by the use of on-site automation

It has been argued elsewhere [9,10] that construction as an activity has a technical dimension as well as an economic dimension. It is not enough to show that a production system is technically effective - the system must be fully commercially viable as well. This later aspect is traditionally more difficult to solve than the former. The original PS system, for instance, solved all the technical problems of building structures but was not sufficiently economically attractive to the wider industry to displace the more established (and possibly more versatile) construction methods.

One of the limiting factors in the PS system process-economics was that it was not flexible enough. However, as argued already, modern manufacturing technology can now overcome, to a large degree, the process versatility and flexibility issues but there is still remains a need for further lowering of costs to foster the adoption of the new re-engineered construction processes as compared to the orthodoxy. To this latter end, it is clear that one must look for yet further ways of cost-reduction and process streamlining so as to make advanced production methods more and more attractive to potential users.

One possible major way of reducing construction costs on building sites is through the use of on-site automation and field robotics and it is here that that the virtues of the PS method become evident. Automation of traditional building processes is, in the author's opinion, currently technically impossible and will remain so for many years. However, if we use the falsework-free PS system as a point of departure the total-site-automation problem becomes relatively straight forward

From a site automation point of view, the original PS concept would seem to be a nearly ideal streamlined production process that eliminates many of the problems of the standard tradesman based construction method. One can see from the photos above that the site is clean and uncluttered. Autonomous vehicle operations around the site are possible and integrated AGV materials delivery is technically feasible. Reinforcement truss installation is a simple, high volume, pick-and-place onto locating spigot task which can be accomplished simply through the use of a robotic manipulator operating from the floor below or from an overhead crane. The use of a one man operated tele-manipulator or CAD controlled robot [5] (cf. fig. 3) would eliminate the rigger from the operation, and would also considerably speed up the operation since no slinging of the load would be necessary . As well, the use of the manipulator would eliminate the need for people to walk on the joists with the possibility of fall through. Dangerous practices (e.g. fig. 3) would thus be eliminated. Similarly the use of a multi-degree of freedom manipulator [10] working from the underside of the deck would eliminate the need for workers to operate between the secondary girders (cf. fig. 2)

Formwork placement and stripping could all be done by a mobile panel handler such as shown in fig 4 working from the underside of the slab.

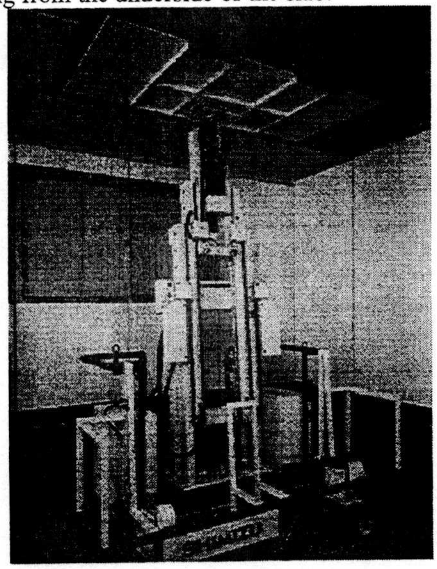

Figure 4 - Example automated panel handler suitable for coffer form handling and general soffit work

Cleaning and oiling of the form panels and rib troughs panels between uses could also be done automatically by use of standard robotically controlled device located on the working floor.

Formwork panels to the vertical column could all be done by a single armed mobile manipulator or (somewhat more futuristically) by co-operative groups of machines [6] for large panel handling.

Small volume placement of concrete to the primary girders could be done with a small automated vibrated conforming plate slipform machine or robotic total-station system [1] or drag screed.

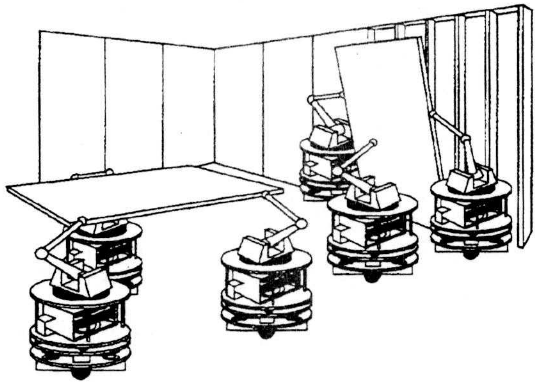

Figure 5 - Co-operative-robot based handling machines

. Concrete delivery in this instance could be via an remotely operable extensible conveyor belt or computer controlled concrete pump. Likewise, infill concrete delivery could be by conveyor or CAD controlled concrete pump with on-surface or gantry mounted fresh concrete screeding and finishing systems. Autonomous concrete power trowelling systems can be used as simple systems for labour free finishing of small local volumes of concrete. This later method would eliminate the need for overtime payments for concrete workers and eliminate the labour mobilisation charges that operate against small volume concrete pouring.

Under this new site automation paradigm the following phases of the construction process that can all technically be 100% automated. Also, no riggers or on deck operatives are required for load handling or fine positioning of materials or fixings.

Work phase	*100% Automatable*
Reinforcement placement and fixing	Yes
Concrete placement and finishing	Yes
Formwork panel and coffer placement	Yes
Formwork panel and coffer stripping	Yes
Formwork panel cleaning and re-oiling	Yes
Formwork panel materials handling	Yes
Armature module materials handling and placement.	Yes
Handling and alignment operations and inter-unit connections	Yes
Mechanical and fire services	Yes
Electrical services	Yes
Air conditioning	Yes
Suspended ceilings	Yes
Facade glazing	Yes

Table 1 - Automatability feasibility check-list

From Table 1, it is clear that this improved process should enable the practical and economical full-automation of generic form R/C process building construction. The central shear core of the building can be supplied relatively easily with an automated and robotised slipforming process supplemented with a CAD controlled concrete pump[1].

7. Features of the economically improved PS system.

The original PS system was proof-tested on over 20 major structures in Australia and was found to be around 'line-ball' as far as economics were concerned relative to orthodox low repetition building-frame construction work. For high repetition work the system was much more economical. The argument here is that if recent advances in flexible manufacture and CAD/CAM and full on-site robotics and field automation technologies could be applied, the overall process would then be some 10-20% cheaper than conventional methods. The system would also be much faster and much less weather sensitive and have better quality control.

Further, by methods that this writer can envisage (such as precision load-control tower cranes [7] with robotic end effectors, site industrial robots, field manipulators [5-9], concrete terramechanics vehicles and so on) it is now considered fully technically realistic to suggest that concrete framed buildings can be erected with a 90% reduction of on-site labour as compared to the orthodox method. Time can be expected to be at least 40% faster than existing - even more if CIM and CAM technologies can be fully implemented.

8. Summary

Automation of the traditional hand-crafted process for reinforced concrete building construction is very difficult due to the highly cluttered and unstructured nature of the process and due to the existence of many highly complex site operations - such as steel reinforcing bar tying - that are very hard to automate. If, however, one can re-engineer the process (perhaps by use of a modified PS method as discussed here) the total automation of reinforced concrete structure production becomes relatively simple. If one can generate clean uncluttered sites with direct access to the work areas by robotic arm equipped autonomous vehicles and if one can arrange high efficiently prefabrication of component reinforcement and efficient automated concrete placement and finishing systems then high efficiency site construction processes are possible.

Given that the original 1970's implementation of the PS method may have been a few percent more expensive than the manual method there is every indication that in the late 1990's, the PS method coupled to modern flexible automation and robotics technology would be now - in absolute terms and including both typical and no-typical building zones - be substantially cheaper than the orthodox man-intensive construction method. This is even more possible since the cost of labour in relation to material and physical capital has increased and the full cost of occupational health and safety injuries on construction are now being taken more seriously. Field robotics technology has great potential for risk reduction in this and other forms of construction [8] and for reducing insurance overheads.

9. Conclusions

This paper has presented a method for the totally automated production of generic-form reinforced concrete framed structures. The method proposed uses extensive off-site and on-site flexible automation and advanced manipulator technology. The method is an evolution from a previously highly successful commercial building system that was used to construct a number of major building in Australia and which was fully economically viable - even in its early-form automation guise. The new full automation method proposed in this paper uses a combination of currently available and proven technology and is technically feasible at the current time. No new technology needs to be developed or invented. Additionally, this new full automation method can now be shown to be clearly economically-superior to orthodox methods of concrete building construction. For these reasons one would expect that full-automation methods should now herald-in a total new era in the history of concrete building construction.

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Appendix A - A Brief Review of the Progressive Strength Concrete-Building-Frame Construction Method

Progressive strength may be considered to be a adoption of the art of bridge building to the manufacture of buildings or more artistically as the adaptation of the spider's way of building structures. In these two arts, the structure is not developed serially but rather progressively with each part acting as a staging for the next part. The philosophy is similar to that used in the creation of suspension bridges.

Taking the bridge building analogy into the context of reinforced concrete construction, one can by noting that in general the vertical elements in a reinforced building generally do not constitute a real problem in the development of a building because the primary loads in vertical element tend to be compressive and even quite new concrete has an appreciable compressive strength. Thus in the creation of columns the member tends to act as its own support system and to need very little in the way of a falsework virtual structure to support it's construction.

In general it is the horizontal members that constitute the problem and which need falsework support in an orthogonal direction.

The core idea of the progressive strength method can be illustrated by supposing that one is faced with bridging over or decking out a 1 or 2-dimensional gap over an area where it is forbidden to place props and one has already access to the tops of a number of "bridge piers". The aim of the construction exercise is to construct the structure using ***only*** the permanent materials or as small an extra amount of strengthening material as possible. Alternatively if supplementary members are required they can be added from above in the form of launching trusses, removable top chords and so on rather then as members added below in the form of props. Members added below the real structure tend to get topologically-trapped by it whereas top added materials can still be accessed.

{The premium for attaining this intrinsic work simplification is a cost in terms of whatever additional permanent reinforcement is needed to make the reinforcing steelwork full load bearing. It is noted however that prop-free operations to the underside of a suspended slab do not preclude the use of top-side falsework. This means that bridge building techniques such as cable-staying can be employed as temporary falsework or strength supplements,. This cable-staying would not be consumed in the process and hence would not be a consumable cost. Again, techniques such as balanced cantilevered construction and devices and other bridging methods such as the topical use of launching trusses are possible.}

Consider now the one-dimensional bridging problem. If one takes a bridge builder's perspective and looks at the gap between column capitals a bridging problems then members can be developed across the gaps by either drop-in-place methods of by placement of members by launching trusses or balanced cantilever construction.

If in this bridge building perspective we are required to build in-situ concrete members using poured concrete that requires formwork then we can take advantage of the fact that in a typical doubly reinforced concrete beam the reinforcement itself is a source of finite strength. More particularly the reinforcing steel that comprises the permanent materials can be formally developed as a load bearing 'cage' or 'truss'. The bars can be welded together to comprise a cast-in place launching truss cum internal falsework member. By using the initial strength of the internal steelwork as a welded-up structure rather than as a set of loose bars. Forms can be supported from this truss and concrete placed (fig 6). The rebar-truss or structural cage is cast-in and lost in the process. Once this member is in place and developing strength it can be used as a falsework component to support another.

In this construction process, it can be seen that one is substituting "welding together of bars" for the supply, erection dismantling and carting away of falsework and parts of the virtual structure. In some ways this may seem a strange substitution but in these days of welding robots, welding is a process that can be done with effectively negligible cost.

In many cases the rebar that constitutes the cast-in situ member is sufficient to carry the weight of forms and a progressive development of the cast-in place concrete. In other cases some supplementary steel may be needed to support the gross weight of hung forms and the self weight of the fresh concrete. Typically the bottom rebar suffices to act as the bottom flange of a girder or truss element but sometimes web-steelwork and top steel additions may be necessary to develop a composite and integrated action rebar structure. In some worst case scenarios it may be necessary to introduce a single mid-span prop to support dead loads. Whilst this defeats to a degree the idea of prop free construction a single prop is still an great advance over a whole virtual-structure. Also the single prop can be developed as an attachment an autonomous vehicle and hence can be part of an fully automated system.

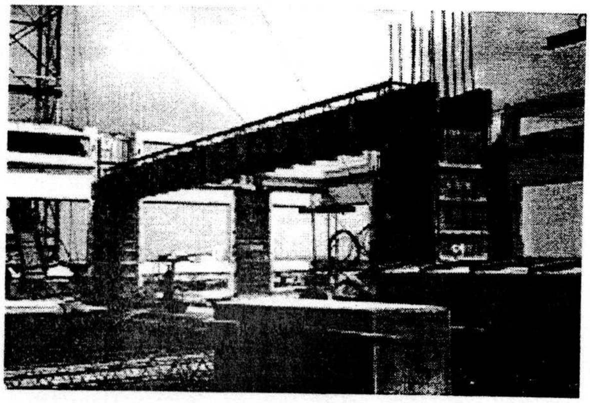

Figure 6 - Prop-free primary beam formwork

Consider now the two-dimensional bridging decking out problem. Once one has the capacity to span between column capitals in a falsework free manner then a two dimensional area can be decked out in a prop-free manner following the process of figure 7.

Moving these ideas into 3 dimensions, it is possible to develop an integrated concrete frame production system wherein a series of prefabricated skeletal members re sequentially and progressively dropped into position in a simple stack building operation to form the armature of the finished structure. The skeletal member assemblage or armature is then strengthened and glued together by the addition of cast-in place concrete supported from forms hung from the armature.. In the final view the skeletal members turn-into the standard reinforcement in the finished frame structure. In this process there is hopefully no compromise on joints and permanent materials consumption.

It is noted that the process of erection of the skeletal member armature is a simple drop into place non-high precision operation that is ideal for automated assembly from above. Such processes are now standard in the robotically manufactured product industry.

In the above process the area above and below the deck is free for mobile machinery access and most of the erection operations can be accomplished from the top only. Those operations that are intrinsic to the process i.e. the placement and removal of form panels to the undersides of the deck can be accomplished in a fully falsework-uncluttered environment.

A distinctive feature of this operation is that the construction process is developed as time staged process in three dimensions. This contrasts to the normal process where progress develops in a vertically stacked layer-by-layer process.

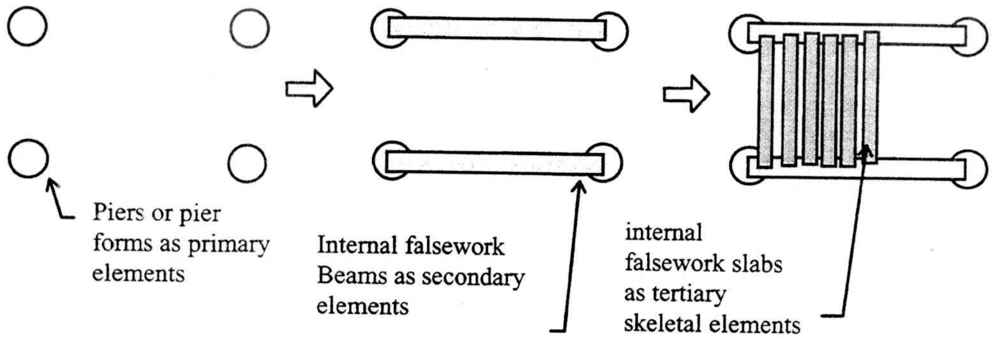

Fig. 7 Plan view of the armature structure erection process before it is progressive integrated by addition of fresh concrete

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