Prestressed hybrids of AAC and HPC

The BCE (Block Composed Element) building system

A conceptual study

Licentiate thesis

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- Preface

This report covers a development of the BCE-system conducted at the department of building engineering, School of Architecture at the Royal institute of technology (KTH), Stockholm. The project has been long due, initiated originally (1990) from an industrial position and supervised throughout by prof Bo Göran Hellers. The technology has been previously exposed and discussed at the third RILEM conference, held in Zürich, on autoclaved aerated concrete, AAC (Hellers & Lundvall, 1992) and further explained in a report from the Swedish University of Agricultural Sciences (Hellers, 1993). In a closing study, Gunnar Rosenborg has mentioned in his book on Siporex 1934-94 (Rosenborg, 1998) about our further development. The revised technology has been presented in a recent paper (Bagheri & Hellers, 2005) and on the CBI info-day 2006-03-16 “Försänd lättbyggnadsteknik”. The fourth conference on autoclaved aerated concrete, held at Kingston, London, in 2005, did not discuss the present technology due to controversy over properties, related to the specific recipe of material.

This report has three parts:

- hybrid concrete elements
- production systems for hybrids
- application and details in building

My personal contribution to the development of the BCE-system began in 1996, by testing the proper combination of concretes, especially the conditions of moisture content to attain the best bond (Bagheri & Hellers, 1997). The results inspired optimism. My next step was to plan the conceptual design of a production facility, the BCE concept for manufacturing pre-stressed building components, which should be simple to operate, practical in quality achievement and limited in investment. This facility may be located next to an AAC block production, as an extension, or close to the building site, if such an arrangement is economical. The blocks are shipped in this case to the site, densely packed and protected, e.g. by plastic shrink wrapping.

The production facility following the BCE-concept requires extra manpower, if compared with an integrated AAC production or an automated concrete element production. On the other hand, a lower investment budget is easier to combine with market flexibility and volume adjustment. Also, if economy permits, the production facility may be developed, automated by using more or less advanced robots, as a next step.

The possibilities of applying hybrid elements in different parts of a building are investigated and demonstrated. This building technology may be developed in combination with surface layers of other materials, to achieve the desired levels of insulation (heat, fire, acoustic, vapour).

The report has been subject to a final seminar supervised by the experienced AAC marketing manager Bo R. (Max) Schmidt on 2005-06-08. He has served in marketing both Ytong and Siporex, the latter as manager and responsible for product design and development. The study has been supported by Cementa AB, Ytong AG (Dieter Hums, Munich) and the School of Architecture, KTH.
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Summary

There is an important potential for a development of a building system, if the present AAC-block plants are completed with high performance concrete and pre-stressing technique. This can be done as a continuation of a present AAC production or in a site factory.

Hybrid cooperation between AAC and concrete is not a new technology. Traditionally, AAC is covered with rendering. The wetted material is first sprayed with cement slurry after which comes lime/cement-based rendering which strengthens the wall and supplies a mechanical protection. AAC blocks can be used as infill members in concrete deck plates and concrete framed walls (Hellers, 1993), in which the shrinkage of the surrounding concrete locks completely the cured blocks into a stable composite.

A good cooperation between AAC and concrete is a requirement for the pre-stressed hybrid. This combination has been investigated with reference to bond and moisture content. The interface must have sufficient bond to supply shear strength to the structural member. Also, the concrete should be suitable for pre-stressing which requires a minimum strength class K40. Here, K60 is applied in order to reduce creep and avoid creep failure of the AAC. A production layout for the purpose is suggested.

This research consists of three parts:

1- **Hybrid concrete elements**
   The principal formulation of hybrids, built on cooperation between two concrete materials, a weak AAC and a strong HPC poured on top, shows that this combination unites the most favourable qualities of the two concretes into a structural element with rational building technology.

   Load-bearing capacity is good, and the fire protection is excellent. Through pre-stressing of the structural concrete, a crack-free behaviour is guaranteed up to the service limit, and deflection from dead weight (incl. floor covering and possibly half the service load) be eliminated. The most important structural elements needed in a building system could be taken as hybrids. In drawings, different members like floor- roof- and wall members, window and door lintels are shown.

2- **Production system for hybrids**
   AAC blocks form a bed containing the pre-stressing steel in slits and on which high performance concrete is poured. Pre-stressing brings the two concretes together. This is especially important for the shear capacity of a building member, by which extra dowels can be omitted. The pre-stressing force is anchored by plates directly against the cured AAC blocks. A special pre-stressing bed is not required. The production is arranged in such a way that necessary equipment (trays, form strips, wedges, locks) are circulated within twenty-four hours. The necessary manpower for this facility is analysed. Normally 8 men are needed per shift.

   A detailed conceptual production layout for a hybrid production plant is included for discussion. See figure 6.2 (suggested production layout).
3- Application in building

The hybrid members are united at joints and through seams. Continuity over connections is achieved by filling seams with mortar grout. Reinforcement may be included to achieve ductility. By a similar method, it is possible to make connections between horizontal and vertical building members. Common connection details are shown in the report. This building method replaces the equivalent method with concrete or AAC members, and it is in fact a coordination between these two.

The maximum span of floor members is up to 9 m. It makes the system suitable for modern residential house production, but also suitable for office buildings, industrial halls and other applications. See attached drawings, part 2 and part 3.
- Sammanfattning (Swedish)

Det finns en betydande potential för utveckling av byggsystem med armerade hybrida konstruktionselement, om befintliga eller nya AAC-fabriker byggs ut med högpresterande betong och förspännningsteknik. Detta kan göras som en fortsättning av en blockproduktion eller som en ny tillverkningsprocess i en fältfabrik nära byggnadsplatsen.

Hybrid samverkan mellan AAC och betong är inte någon ny teknik. Normalt används puts för fasad på en yta av AAC. Lättbetongen vätes, grundas med cement slamning och sprejas med KC- baserad puts, som har god vidhäftning och ger tillfredsställande hållfasthet och som också skyddar väggen mot mekaniska stötar. AAC block kan användas som utfyllnad (sparkropsteknik) i betongplattor och i väggar av betongramar (Hellers, 1993), där betongens krympning runt den härade lättbetongen läser fast blocken till en stabil komposit.


Detta forskningsarbete omfattar tre delar:

1- hybrida betongelement

Den principiella uppbyggnaden av hybrider, med samverkan mellan en svag lättny tan och pågjuten högpresterande betong, visar att kombinationen förenar det bästa hos två betonger i ett byggnadselement med rationell byggnadsteknik.


2- produktionssystem för hybrider

3- tillämpning i byggnad


Spännviddsbegränsningen om 9 meter gör systemet anpassat för bostadsproduktion men också lämpligt för kontorshus och industrihallar mm. Se bilagor, part 2 och part 3.
1-Introduction
Since Ytong closed its plant at Kvarntorp in January 2004, there is no domestic production of AAC in Sweden. The last manual is from 1993. But Ytong remains a major international producer. Siporex is still marketed as a brand name in many regions of Europe such as Lithuania and France, and in the Americas. The differences between the original compositions have vanished as the recipe is now practically the same, based on the Siporex recipe (Nygren, 1997). This change has been commented also by Rosenborg (Rosenborg, 1998). The Swedish AAC market is supplied by import from other countries, from the Danish H+H Celcon A/S (owner of the modern production plant in Finland at Ikaalinen, and several plants in other countries), from Ytong in Germany and Poland and also from the independent Aeroc plant in Estonia. Specialized builders, such as Piradoff, are importing privately for single projects, of high architectural standard on the Swedish market.

The total use of AAC is growing globally. This growth is especially strong in the USA and in Asia, two market regions with an enormous capacity for expansion of AAC, as a replacement for wood and steel. Also, the efficient use of binding agents (cement, lime, PFA) in AAC makes the material much superior to foam concrete of the on-site type (c.f. Neopor; Masanja, 2006).

Three international companies, Ytong, Hebel and H+H Celcon, are now engaged in exploiting the market for AAC, using well-known arguments. AAC has demonstrated its benefits for more than 70 years, AAC has a relatively high heat and fire-insulation capacity, AAC structural members with reinforcement can be combined in an integrated production with non-reinforced block material, etc. The fact is that the named qualities are not quite sufficient for modern building requirements in the temperate climate zone. Also, the integrated production of reinforced and block materials requires a qualified plant facility with an advanced reinforcement technology. Only in times of a durable building boom is the investment justified. So, on the European market, the proportion of reinforced material is still less than 20%, which is close to a failure.

Another disadvantage is that in order to maintain and supply a full building system, it is necessary to keep 3,600 different products in stock. The required storage volume is not only huge, it is costly and situated, normally close to the production plant. It increases the total cost of the building system. Besides, at visits to existing stores it is not unusual to find products, which are 20 years old or more.

The project presents a new building system of concrete hybrids, combining the best properties of HPC (High Performance Concrete) and AAC (Autoclaved Aerated Concrete). The concept of BCE (Block Composed Element) forms a new way of prefabricating structural elements, a development either from the AAC or from the HPC side. Coming from the AAC side, the BCE technology holds an upgrading of the capacity. Coming from the HPC side, the BCE technology holds a substantial reduction of reinforcement and concrete use. It connects to an early trend a century ago of applying the qualified material, concrete, in a precise and intelligent way, (Hennebique construction; Berg, 2003). Also, the properties of hybrids may well be advantageous for other purposes, like heat regulation.

Production of AAC structural members by this method will be more flexible and cheaper by comparison with traditional reinforcement. No reinforced product is manufactured unless
ordered. The demand for investment is reduced by which the basic production of non-reinforced material is stimulated. At the same time, the need for capital binding is lower.
2. Autoclaved Aerated Concrete
2.1 History

Autoclaving as a means of activating and stabilising a limited proportion of binding agent in a mineral composite was patented in Germany as early as in 1880. Autoclaved aerated concrete (AAC) was invented and developed between 1924 – 1929, when it was first launched on the Swedish market. The inventor was an architect, Axel Eriksson. He used the "lime recipe" for his AAC (Ytong), which contained lime and ground slate, besides the foaming agent, aluminium powder, whose foaming effect was discovered already in 1914. An alternative, the so called cement recipe for AAC, was taken up by Lennart Forsén and Ivar Eklund in 1930. They applied for a patent in 1933 and the material was launched on the market in 1934 (Siporex). The patent was granted in 1937.

At its peak in the late 1960s, the production of AAC from several domestic producers (mainly Ytong and Siporex) amounted to 1.6 Mm³ per year in Sweden, including minor export volumes. Now (2006) the use of AAC on the Swedish market is around 0.1 Mm³, but growing.

After the introduction, AAC was spread around the world by a small number of international companies selling licenses or by forming subsidiary companies. Initially, the material was produced close to the customer. A recent development is the trade of building materials, including AAC, across borders. Such exchange is an evidence of the material’s popularity and wide acceptance.

A rapid spread of the AAC technology occurred in 1950-75 (Dubral, 1992). Then, there came a period of limited expansion up to around 1990. Now, the conditions are becoming ripe for a radical expansion outside Europe. In countries like the US and in several Asian states the alternatives, like wood, are getting scarce and steel is becoming too expensive to use in everyday applications.

The production of AAC in Western Europe (14 countries) was 8.65 Mm³ in 1991 (Dubral, 1992). The same year, the production capacity in Eastern Europe (7 countries) was 22–24 Mm³ (Russia is the single largest market for AAC) (ehouseplans.com, 2000). With an assumption that the capacity is covered in practice to 50-55%, it means that an European total at the time was around 20 Mm³ (21 countries). In 2004, the production of AAC in the 17 EAACA countries (the European Autoclaved Aerated Concrete Association) was 18 Mm³, (Schramm, 2006). Considering the difference in number of countries, it is a fair estimate that the production in Europe stayed constant around 20 Mm³ per year in the period 1990-2005.

The global production volume of AAC was 31 Mm³ in 1995 from 250 factories around the world (Emerging Construction Technologies, Purdue University & William V. Abbate, Hebel, USA). As many as 70-80 of these were in China (Husbyggnad, 2/94). The average output from a factory was 125,000 m³ per year. The volume outside Europe was 11 Mm³. In 2004 the worldwide production was more than 75 Mm³ from 300 factories, and almost 20 new plants are said to be opened every year (Budwell International, 2004). So, the output from a single factory was on average 250,000 m³ per year, or doubled over ten years from 1995-2004. The 20 new plants will contribute another 5 Mm³ of AAC per year. The volume outside Europe has grown from 11 to 55 Mm³ per year, or by a factor 5 within ten years. Thus, the average growth was 4.4 Mm³ per year, slightly less than the present growth rate. The amazing
establishment of AAC production is located outside Europe in countries like the USA, China and India in Asia (Amvic Building System ICF). With the present rate of growth, the capacity will exceed 100 Mm$^3$ per year before 2010.

The market for building materials in the US is a good example. Steel was replacing wood in the 1990s, for scarcity of lumber (Stålbyggnadsinstitutet, 1995) and now AAC, which is not so price sensitive to international trends, is taking over from steel.

Building members of reinforced AAC were first produced in 1933 in Sweden (25 år Ytong, 1954), while reinforced Siporex was introduced the year after (1934). The two producers have later been identified primarily with block production (Ytong) and reinforced building members (Siporex). Internationally, the identity of Siporex has been taken over with time by Hebel, which is promoting a full building system based on AAC.

The rivalry between producers of blocks and producers of building systems reflects the cultural difference between those favouring a semi-manufacturing position and the manufacturers who promote full programs. The purpose of BCE, the topic of the present dissertation, is to bridge this gap.

2.2 Manufacturing process, including non-tensioned reinforcement - production of AAC

AAC is produced in block factories or in factories with an integrated reinforcement technology, which allows for a manufacturing of any building members, such as deck and roof elements, wall units and lintels beside blocks. In volume, the production of advanced components has remained, however, a minor part of the total. Dubral (1992) mentions that the proportion was only 16% in western Europe in 1991, which proves that the technology has not been very convincing to the customers. Sweden was an exception with a proportion of reinforced material from Siporex above 60% in 1964 (Rosenborg, 1998). Also, the investment required for building an integrated production unit is more than twice that of a simple block factory, which has a significant effect on the market appearance (Jean Tyrèus, 1974). Either a mass-producing AAC-block unit, or a sophisticated production of a variety of building components.

Also, the process time differs significantly for various products, reinforced members needing almost twice the time for pressure rise and curing in autoclaves than blocks (ACCOA, 2006).

Blocks have remained the basic and dominant product. The large size, the ease to adjust the format and the low weight of the blocks make them suitable for any sort of masonry. Also, the high precision of their geometry allows for using thin bed joints of 1 – 3 mm.

But blocks alone can not constitute a building system, so they have been used in combination with structural members of other materials, such as concrete, wood and steel. Such combinations are often rather crude, not considering the heat bridges (concrete, steel) or the durability conflict (wood). A block producer, Celcon gives an example of this conflict in a Practical guide, 1995, where wood lintels are supported directly on masonry wall of AAC.

With a recipe based on silicious sand, the thermal elongation of steel is $1.15 \times 10^{-5}/°C$, whereas the AAC is $0.85 \times 10^{-5}/°C$. So, after cooling from the autoclaving (or curing)
temperature of 200°C to ambient temperature, the reinforced section is slightly prestressed, which helps suppress the inclination of crack formation (Dahl, 1991; Wasteson, 2003). With a full PFA-based recipe, this effect seems to be lost (Dahl, 1997) leading to longitudinal cracking. Recently, Rasmusen of H+H Celcon A/S stated that this difficulty had been overcome. It is likely that the recipe has then been supplied with sintered magnesia (MgO), a method to suppress thermal elongation, originally developed by Ytong. Or, even more likely that the recipe has been modified to contain a part of sand, as stated by Aircrrete, 2005.

Previous tests have indicated that the effect of prestressing was still in place with a recipe of 70/30 of PFA/sand, which maintained the full strength of the material, whereas a further increase of PFA up to 100% reduces the strength for higher densities by 10% confirmed in the Celcon product guide, 1991. The matter of thermal elongation does not refer to blocks.

AAC is produced to several standard (dry) densities. In Europe these go from 350 to 750 kg/m$^3$ (350, 400, 450, 500, 600, 700, 750). The lowest density has a conductivity of 0.08 W/mK. The Swedish AAC manual from 1993 starts with 400, continues with 450, 500 and goes to 600 (750) kg/m$^3$. The lowest density has the lowest value of conductivity ($\lambda = 0.10$ W/mK), while the highest density has the highest compressive strength ($f_c = 5.0 (8.5)$ N/mm$^2$).

**Fig. 2.1.** Integrated production process of AAC blocks and AAC construction members (reinforced)

Reference: "Lättbetong handbok" 1993
2.3. Material properties of interest to hybrid function

In general, AAC in cured form is a material that is easy to work, to drill or mill, to saw (if you have a hard tool saw), to cut, to slit and scrape. Recesses are cut by hand or by handy machines.

Even more rational is to work the material in uncured form, by wet – milling and sawing. But the material becomes more fragile in transportation and sensitive to geometrical variation. This possibility has not been further developed (in connection with the BCE technology).

It is practical to transport AAC blocks on standard palletts, wrapped in shrink plastic foil. Also the possibility to pack such parallelepiped shaped palletts tightly on the platform of a truck is logistically superior to the common transportation of a variety of AAC products. A conclusion is that whenever feasible (large project), a site production of BCE is advisable.

The ease to work the AAC material can be used to shape any product to desired form, also in hybrid function with PCC. A product may be divided, or cut in lengths, after curing using sharp tools. Also, the milling of tongue and groove in the cured AAC material requires modern and hard-wearing sintered carbide equipment.

- Advantages of AAC-material
  - an inorganic material, which after autoclave curing is stable and ready to work
  - raw material supply for production can be by-products like PFA class F or finely grained silicious sand or filler, well graded to purpose and quality checked
  - mineral binder of cement/lime is added in accordance with a well defined and economical recipe
  - the material is reactive to moisture, both in production and application
  - the material is moderate in moisture related shrinkage and in creep
  - the material is highly durable in most climate environments and it has low emissions
  - the energy steam for autoclaving may be taken from the down-side of a utility plant with powder coal feeding (binding temperature is slightly less than 200°C)

- The problems with AAC may be compiled in the following way:
  - heat insulation property is not quite up to the requirements for residential purposes in the temperate zone
  - the acoustic insulation property is not up to modern standard requirements
  - the compressive strength of the material is related to density and for light weight it is fairly low
  - the load bearing capacity of reinforced horizontal members (floor, roof) is not very high
  - reinforcement of horizontal members requires much steel, because compressive steel must always be applied, like shear reinforcement and extra bars for anchorage
  - corrosion protection requires a bath of chemicals to cover the steel
  - production technology is undeveloped and requires an extensive storage of different building members.
- Moisture dynamics of AAC

AAC is a moisture dynamic and hydrophilic material. It absorbs moisture easily, either from ambient air or by capillary suction from any source of liquid water. A moist atmosphere may enrich the material into condensation. Also, the material delivers moisture easily to ambient air. In applications, the important condition is that the material must experience long enough periods to dry out between periods of moisture absorption. For safety, there must also be a margin so that the material does not build up an increasing level of moisture over time.

Normally, there is no need for a vapour barrier on the inside of a wall, except when the atmosphere there is constantly wet, (stables, breweries etc.) The material is often delivered with a moisture content of 30%, which is reduced to an equilibrium level (of 3-6%) with the ambient atmosphere within a year. Of course, this figure depends on many conditions like geometry, weather conditions, protection and more.

High Performance Concrete (HPC) and AAC are both cementitious and porous materials on a mineral basis. In comparison, AAC has a far higher immediate capillary action. In combining these materials, the purpose is to create as good bond as possible in the transition zone in order to ensure that the materials interact in bending. So, the AAC must be enriched with water to reduce the capillary intensity and serve the concrete in curing with moisture.

In the natural desiccation of the hybrid, the two concretes will shrink somewhat differently. This difference must be checked with reference to up-coming shear stresses, which must not threaten the survival of internal bond between the materials. The difference in moduli of elasticity is more than 20, \( n = 21.2 \). The shrinkage of concrete (K60) is at the most 0.5 pro mille, whereas for light weight concrete it is at the most 0.2 pro mille. The induced compression of the light weight concrete will be less than 0.5 N/mm\(^2\), which causes no problem. The adjacent shear stress is low (approx. <0.1 N/mm\(^2\)). A correct calculation requires FEM-calculation, which is outside the scope of the present thesis. No experience supports that the bond would be lost in practice and not in this project.

2.4. The motives for a general expansion of AAC

The inorganic raw materials for producing AAC are simple and readily accessible around the world. Transportation costs can be kept low. The materials are silicious filler (sand, PFA, sand/PFA), water, mineral binder (cement, lime, PFA) and foaming powder (aluminium).

The product has proved its adjustability, capacity and durability in different climate zones. It functions well in the cold climate of Scandinavia and Russia, in the humid climate along the Atlantic coast, in the hot climate of southern Europe, in northern Africa and further south, also in combination with humidity. The critical condition is that the material must always have the opportunity to dry out between wet periods. This is a matter of building physics, and considering such restrictions, there is always a way to use AAC. Concluding, there are excellent possibilities for internationalising the production of AAC and its extension to hybrid members. A difficulty may arise in producing HPC of sufficient quality, K60. But the volume of this material is so limited in the process that it may not pose an insuperable problem.
- PFA (fly ash) as filler
Fly ash is a waste material from powder coal combustion in utility plants for producing electricity and district heating. It is trapped in electrostatic filters in an environmental protection process. Any coal contains between 5 and 15% incombustible mineral, which ends up in these filters.

The spread of the AAC-technology is favoured by the development of a fly ash based recipe. Milling is not needed. This idea was implemented by Celcon Ltd., England, already in the 1950s. But the technology has been offered also by the old producers, like Siporex, in China (Husbyggaren 2/94). Replacing all silicious sand by PFA (100%) leads to a thermal elongation which can be accommodated only by blocks. Stopping at 70% reduces the elongation to a point where reinforced products are possible. Now, with the BCE-technology it is possible to apply blocks of 100% PFA in making building members. In fact, it is a practical prerequisite for a full conversion to PFA to implement BCE. Besides, PFA contributes to the binding effect (Harris, 1993).

The amount of generated PFA poses problems in several countries, e.g. the USA, where 70 Mtons are generated annually (Bhatty & Gajda, 2005). The use of this resource in secondary products or processes has been growing slowly, from 15-20% in 1986 to some 38% in 2003. So, more than 40 Mtons of PFA are still dumped annually, which causes environmental concern. The cost for disposal of fly ash was $20/ton (EPRI, 1999), a cost which is known to increase rapidly with the environmental legislation. With an average weight of 350 kg PFA per m³ the potential for producing AAC in the USA with this currently wasted material is more than 120 Mm³ per year. A practical target may be 50 Mm³ per year, which is close to 30 times the volume at which AAC once peaked in Sweden, 1968.

There are countries in Europe, like the Netherlands (Apul, Gardner & Eighmy, 2005) and Denmark where all the fly ash is reused in making secondary products (pellets, cement …).

- energy saving
The amount of energy for producing AAC including the process of raw materials is approximately 275 kWh/m³ or 1000 MJ/m³ (ACCOA, 2006). Any figure on energy input must be subject to consideration, as current prices are developing. And producing AAC is not trivial, from an energy standpoint. But an arrangement for using of heat by-product between 3 different plants (electricity power plant, AAC block plant, hybrid plant) can reduce this energy consumption significantly (see section 6.4).
3. Concrete
3.1. High Performance Concrete (HPC)

High Performance Concrete is made of the same ingredients as normal concrete, only with a higher precision of aggregates and more cement with a lower water to cement ratio. The trivial definition of HPC relates to the strength domain between K80 to K120. True, HPC means a concrete of high strength but moreover, a concrete of refined composition which meets a specific requirement. In the present context, two HPC concretes are used, one for thin layers on the hybrid, the other for massive bodies of lintels.

The reason for using HPC was originally to reduce weight and geometry in connection with multi-storey buildings, competing with steel. Now, this ambition proved obscure considering the ease at which steel could improve in quality and strength. Hybrids offer a much more interesting alternative, where HPC is poured in thin sections to complete the geometry. The concrete is used only where it is needed for structural capacity. Other functions are then possible to integrate with the hybrid, such as heat and fire insulation, low weight and accessibility etc.

3.2. Properties of interest to hybrid function
- history of in-fill body technique

Before the 20th century, all buildings were built of stone, brick and lumber. The decay started from underneath. Foundations were difficult to build and maintain, due to groundwater and stability of earth. So, when concrete became available, it is small wonder that it was primarily used for foundations (Berg, 2003). Such technology was well established by 1890. The production of cement started in the 1870s and mixers for making on-site concrete were soon to follow.

The use of concrete expanded upwards in buildings, completing and replacing gradually the traditional materials. The pace of this development was dictated by the relative price level but also by building regulations. Concrete was relatively expensive and used only where it was most needed. This inspired a development of in-fill structures, generally floor structures, where concrete was embedding other materials such as hollow core bricks and concrete blocks as well as wooden boxes. The purpose of concrete was to serve as compressive and reinforcement anchoring material. Such in-fill floors had a relatively low dead weight, which underlined the economical feature.

So, when AAC blocks entered the market in 1929, the technology was already there. This can be seen in textbooks (Kreüger, 1931), where two alternatives for an in-fill floor with AAC blocks are illustrated. The reasons for putting an extra piece of AAC underneath the concrete webs are twofold, to increase the fire resistance and to avoid cracking of the underneath ceiling plaster. In performing this structure, it was soon observed that the AAC needed a good watering before pouring the concrete, in order to attain a reliable joint performance.
As concrete became cheaper, in relative terms, in-fill structures were gradually abandoned. The need for better acoustic insulation was satisfied with monolithic concrete structures, such as massive floor plates, which were a standard concept from around 1960. (Such plates had a depth of 160 mm, a figure which has grown by at least 100 mm until today). Not even for prefabricated concrete products, where the technology might have been maintained, was the in-fill technology of interest.

Monolithic structures, floor and wall members of massive concrete, are dominant in the building technology of today. This is true for both genuine concrete (PCC) and for AAC. The purpose of the present work is to point at a new possibility of combination.

- Restrictions on the environment, natural resources

For a long time, gravel in Sweden has been considered a natural resource of almost unlimited affability. The top year, the total consumption was 110 Mtons in the country (more than 10 tons per head! Only the Finns were worse with a top figure at 15 tons per head). Now, there is an agreement between Byggbranschens kretslöpsråd (an optional body of industrialists from the building sector promoting recycling) and the government to implement a sharp reduction, explained in detail by Länsstyrelsens i Stockholms län, Faktablåd, 2003. At present, the annual use of gravel is 30 Mtons. It must come down to 12 Mtons by 2010 and further down to just 3 Mtons by 2020. This is of course far less than what is needed in the Swedish concrete industry alone (Hultqvist, 2000), and the industry policy is to fill the gap with crushed rock material, (Sandahl, 2006). The recipe of concrete has been adjusted to accommodate this change. Also, the Swedish standard portland cement (Byggcemement) was developed for this purpose.
At present, the global cement production is increasing by 5% per year. It is a runaway development indicating a threefold increase between 1990, the year when the Kyoto protocol was adopted, and 2020 (McLeod, 2005). There are three options to handle this scenario:

- reduce emissions within the existing industry
- replace cement binder with viable alternatives, where possible
- revise your structures to higher capacity, using less cement and prestressed steel

The present BCE-technology belongs to the third option. In fact, McLeod points at AAC as a material solution to the problem of reducing the dependence on cement. Considering that the current proportion of volumes, on a global scale, is more than 40 in favour of ordinary concrete, this scenario would require a drastic change of patterns, which does not seem likely. The likelihood for a rapid change to the BCE-technology is better, in my opinion, considering its capacity despite limited stakes.

The ambition to use concrete in a precise and limited way is also dictated by the fact that the material can not, in practice, be recycled. Crushed concrete as aggregates in new concrete implies a major step down in quality, which can be compensated to some extent by adding cement binder above proportion. Recycling means an expensive composite of limited quality or a low quality concrete to be used in unqualified environments, such as road bodies.
4. Hybrids of AAC and HPC
4.1 Joints between AAC and HPC – performance tests

The key to a full composite interaction between the concretes, AAC and HPC, lies with the bond and the shear strengths. Both must be high and durable in a practical case. Anyone familiar with concrete overlays is aware that the result is very sensitive to deficiencies of the base, such as dust from abrasion or spills of any kind. Careful cleaning combined with a primer are needed for balancing variations. In the present case the situation is complicated also by the hygrophilic nature of the base material, AAC. It is a fair hypothesis that the resulting capacity of the composite is depending on the interaction through the moisture conditions of both materials, the AAC base and the concrete grout. The compacting and the curing conditions of the concrete overlay also count.

A strong and reliable combination of concrete and AAC is necessary for making a hybrid member. A series of tests was conducted in 1997 to evaluate the important parameters dictating the boundary conditions between the two cement-based materials, AAC and construction concrete (Bagheri & Hellers, 1998).

Such studied parameters were the moisture ratio in AAC, the concrete recipe, water percentage in the concrete, priming of the AAC surface prior to concreting, concrete curing period besides other relevant observations.

The quality category of AAC in the tests was density 500. Four different moisture ratios (10, 20, 30, 40%) were chosen, considering that the level at delivery is around 30% or less. The competition for moisture between the two concretes decides the quality of the bond. A deficiency may have a detrimental influence on the result.

Four different kinds of concrete combinations were chosen. The blocks for testing were under plastic cover in curing periods of 3 or 14 days before conducting bond and shear tests (Bagheri & Hellers, 1998).

Results of bond and shear tests

Concluding the test results, the two parameters, considering the specific test methods, can each attain a maximum level of 13% of $f_c$, or the nominal characteristic strength of the AAC-material in compression (Lättbetong manual, 1993). A general observation is that the curing time has a minor influence on the results. It is possible to speculate whether this may be due to shrinkage effects, which could prevent long-term strength gain. On the other hand, an extension in time does not seem to damage the bond or the capacity in shear.

The test results raised optimism. It is possible to establish a strong connection between AAC and concrete from a relatively high level of moisture in AAC and using a low viscosity concrete. The method requires care in performance and precision in time. But precision to attain high quality products is not unusual in advanced industries of to-day, also for producing building materials. And using new technical instruments, sometimes semi-automatic, for controlling the conditions, like the critical moisture in AAC, can be a great help in the manufacturing process.
Fig. 4.1. A sample of bond test

Fig. 4.2. A sample of shear test
4.2 Prefabrication in the building process, arguments

Many factors have influence on the building costs. The traditional balance would be that material was one third, labour another third, while the cost of capital amounted to the last third of the total. Over the last years, the cost of capital has been relatively low, while the costs of labour and materials have increased significantly.

The first steps of rationalization within the building industry were taken before WW1, in the spirit of Taylor, who died in 1915. The message to the Swedish industry came with the post-taylorists, such as Frank B. Gilbreth, who had a strong influence on prof Carl Forssell. His long teaching at KTH was a pioneering effort in intellectual analysis of the building production.

Ever since WW2 the question of industrialization within the building sector has been raised in Sweden, time and again. From the beginning, it was thought to go without saying that a conversion to prefabricated products would lead to a cost reduction. This assumption was tested on a large scale within the so called million dwelling program, realized in the country 1965-74, when 15% of the production was prefabricated. It was not possible to draw any strong conclusions from this period. But the tradition of on-site craft was finally broken.

The objection against the building industry for being old-fashioned was heard again in the 1980s, due to the massive modernization, no doubt, of the large mechanical industry. Why could not building components be fabricated the same way, in-doors and subject to the same quality control? Well, the experience was not on the side of the industrialists. Several production units, among those a number of integrated AAC-facilities, had been abandoned in the past, due to a decline in the market and failing quality of the products.

Gradually, the quality control systems were established and the remaining prefab industries met a growing market. Again, the discussion was raised whether a prefab production could hold back the cost increase. In one well-designed case, it was shown by comparison that prefabrication led to a reduction of total costs by 5% (Paus, 1997).

Three circumstances are now dictating the immediate future, cost, quality achievement in products, from single components to complete buildings, and lack of labour. True, courses on handicraft are attracting youngsters again, but the skills on the building site are dwindling. The quality achievements are stimulated by prefabrication. The potential for cost control is stimulated by industrial conditions. But the building industry must take responsibility for its own future. Only recently (May 2006) was building excluded from the government initiative over strategic industrial research in the country. Obviously, the 7.2% of the working force active in the building sector must win the confidence of the government by moving into the high-tech sector. The BCE-system may be one answer to this challenge.

Inevitably, the industrial influence over the building process will grow, also due to the fact that the products become more and more advanced, which prevents local, or on-site, production. A transition to industrial building production should be considered as a transition to a more coordinating and rationalized process, and not as a transition to a new building technology, even if such a step could be a consequence or a requirement (Byggkostnadsdelegationen, 2000).
4.3 Properties of interest to hybrid function

A hybrid of AAC, HPC and a pre-stressing reinforcement combines several functions, taken from the different components. At best, the combination may well surpass every single component. The hybrid must be designed in such a way that it makes the most of the input, so that the cumulative advantages of all contributing materials are developed.

Major advantages of the materials are:

1- AAC is used for its stability of dimensions, heat insulation (low conductivity), fire resistance and moisture absorption.
2- HPC is used for its high strength, small dimensions, low creep, economy of ingredients
3- Prestressing reinforcement is used for its capacity to strengthen a long building member, with a small amount of steel

The following properties form the basic motives for use of a hybrid system:

- **Fire resistance**
  Most concrete beams are left unprotected against fire. (Traditionally, concrete was a fire protective material applied around steel! The effect of concrete was to delay the heat wave from reaching the steel bars until counter-actions could be taken.) Now, acoustic absorbents, with mineral wool lying in trays of perforated steel or gypsum plate, serve as fire protection layers. This applies to hollow core members, which have little fire resistance, while hybrid members have a protective layer of AAC and a concrete cover under the pre-stressing bars. The fire protection of a hybrid is also superior, by an estimated factor two (Bohnemann, 1993), to a reinforced non-tensioned AAC-member. The cold-drawn reinforcement in any pre-stressed member is sensitive to elevated temperatures.

- **Acoustic insulation**
  The quality of acoustic insulation is of growing importance in modern building technology. It is reflected in the fact that there are now four quality classes in the current European standard, A – D, of which the Swedish minimum is class C. More and more dwellings are now designed to a higher performance, in most cases class B and sometimes even class A in order to strengthen the marketing of acoustic insulation. It refers to both sound insulation and impact noise. The value of a hybrid member according to table in section 4.4 is taken from a personal estimate by prof Sten Ljunggren, 1997. Reducing the impact noise effect requires the inclusion of a hard pressed mineral wool membrane on top of the structure member. The membrane is covered by another layer of self compacting grout.

- **Heat insulation**
  The insulation quality of a prestressed hybrid is worse than for a genuine AAC member. On the other hand, the insulation quality is not really up-to-date anyway, so a complementary layer of high-insulating material, like mineral-wool, on top of a roof member, is required. In the temperate zone, a modern value of the resistance against heat transfer would be 5 m² K/W, which would require an addition of 150 mm wool.
- Separation of functions
The tendency of current building technology is to separate functions. This requires access to several building materials and the skill to combine them correctly, in relevance with the laws of building physics. For further discussion on this, see section 4.5.

- Concrete saving
Using a hybrid of concrete and AAC leads to a considerable saving of concrete in comparison with hollow core or massive members. Going to the limit of span, 9 m, under extreme load, the reduction is around 50%, and for shorter span and less load the reduction is higher. If the compressive zone is omitted, like in walls, the reduction is up to 85%. Comparing with a hollow core member, it is obvious that the cost of concrete saving is expressed in the reduction of a maximum height/depth relation, from 45 for hollow core to 30 for a hybrid member. Extending to 100% saving with a traditional AAC-member the relation is cut to 25.

- Price estimates
Price estimation is not specified. Indications are that the price level would be the same for all three alternatives.

4.4 From AAC blocks to finished products by prestressing
The green blocks have enough strength to resist the prestressing force. There is no need for a pre-stressing bed with internal resistance capacity. But longer members must be clamped when pre-stressed to prevent upward buckling.

In principle, the physical storage is rationalized by a sharp limitation of the number of blocks. Also, the proportion of block sizes can be easily adjusted in the running production, as the storage is maintained. The amount of tied capital is limited by the semi-manufactured products.

The BCE-method implies more manual engagement and manpower. In many countries, this is not an unfavourable condition, since it increases employment and helps educate the working forces. By the purpose to build good and healthy homes for as many people as possible, the spread of the method around the world is inspired. The technology is applicable, independent of level of society, both in the USA and in developing countries.

- Comparison with other structures of similar materials
Comparing the hybrid structure with other structures of similar materials may reveal significant differences. The two closest alternatives are:
1- Reinforced (unstressed) full AAC member (dens. 500)
2- Hollow core concrete member, made of HPC (high performance concrete), extruded around prestressed strands on a long bed. This member is to be completed with extra acoustic-, heat- and fire insulation materials.
Comparing table between AAC member with unstressed reinforcement, hollow core concrete member and hybrid floor deck member:

<table>
<thead>
<tr>
<th>Member</th>
<th>Unit</th>
<th>AAC member with unstressed reinforcement</th>
<th>Hollow core concrete member</th>
<th>Hybrid of concrete and AAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max length</td>
<td>m</td>
<td>7.5</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Weight</td>
<td>kN/m²</td>
<td>1.5</td>
<td>2.9</td>
<td>2.1 – 2.9 *</td>
</tr>
<tr>
<td>Fire resistance</td>
<td>REI</td>
<td>EI 30</td>
<td>EI 15</td>
<td>EI 60</td>
</tr>
<tr>
<td>Sound insulation (air)</td>
<td>Rw dB</td>
<td>40</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>Moisture absorption</td>
<td>l/m²</td>
<td>85</td>
<td>10</td>
<td>85</td>
</tr>
<tr>
<td>Heat transfer resistance</td>
<td>m² K/W</td>
<td>2</td>
<td>0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Heat penetration velocity</td>
<td>m²/h</td>
<td>0.9 x 10⁻³</td>
<td>2.7 x 10⁻³</td>
<td>0.9 – 2.7 x 10⁻³</td>
</tr>
<tr>
<td>Heat storage</td>
<td>kWh/m².K</td>
<td>45 x 10⁻³</td>
<td>70 x 10⁻³</td>
<td>30 – 75 x 10⁻³</td>
</tr>
<tr>
<td>Floor member span</td>
<td>m</td>
<td>4.5 – 7.5</td>
<td>5.0 – 9.0</td>
<td>6.0 – 9.0</td>
</tr>
<tr>
<td>Concrete saving</td>
<td>%</td>
<td>100%</td>
<td>_</td>
<td>≥50 - 85%</td>
</tr>
</tbody>
</table>

*The first number is short span and low variable load, the second number indicates a maximum span and high variable load.

Fig. 4.3. A comparison between hybrids, full AAC and hollow core concrete members
Fig. 4.4. Combination of blocks can be done in both the horizontal and vertical directions.
Fig. 4.5. Horizontal member of blocks under prestressing

Fig. 4.6. Floor deck member of AAC blocks with concrete pour
Fig. 4.7. Wall member of AAC blocks, prestressing may increase the wall’s capacity (Eccentrically compressed column)

Fig. 4.8. Wall member of AAC blocks with prestressing reinforcement bars, Concrete pours in milled channels
4.5. The intrusion velocity of heat – heat storage capacity

A hybrid of concrete on top of AAC contains a separation in the important relation between heat penetration and storage. The top layer of concrete is quickly penetrated, while the heat capacity is high but the storage, due to the small depth, is limited. This would be favourable in combination with a modern floor-heating system, which needs a quick response function to operate within tight temperature limits.

4.6 Theoretical model of interaction, limits

The model of design has been described in short by Hellers & Lundvall (1992) and by Hellers (1993). It is of basic importance to understand in this connection the deformation behaviour of a prestressed member, figure 4.9. The relation between deformation and load is linear up to the service load level, above which the prestressed section starts to open and the relation becomes unlinear up to an asymptotic approach to the failure load. The position of prestressing strands can be designed to eliminate deformation under the dead weight, or the deflection of half the service load including the dead weight.

The stress distribution at design load level is demonstrated in figure 4.10. The whole section is active in that the bottom fibre has zero stress. The stress distribution at prestress, i.e. after the strands have been prestressed with the member lying on the bed, shows that the HPC top zone is under tensile stress, which is compensated by including unstressed mesh reinforcement.

Figure 4.11 shows the stress distribution at failure load, when the cross-section is fully open. The depth of the compressed zone is designed to accommodate a force, equal to the prestressing force. The details of design are outlined by Hellers (1993).

Fig. 4.9. The position of prestressing cables may be chosen to eliminate deflection of dead weight, or deflection of half the service load (including the total dead weight).
4.7. Long term influence of creep

From figure 4.12, it is clear that creep factor for AAC, density 500, is rather low, in fact around 1 (steady creep). It may seem surprising that it is not higher but the low factor indicates that the material is chemically stable and does not permit any large flow under stress. The short term stress distribution between interactive concretes is basic in design. To stabilize this distribution over time the creep factors of two materials must be equal, which calls for a PCC of the cube strength K55, see figure 4.13. Considering the risk of stress transmission from PCC to AAC, which could readily lead to stress failure of the weak component, it is suggested here that we choose K60 to allow for a safety margin. The risk combined with stresses over long time transmitted from AAC to PCC is, of course, far less.
4.8. Durability and fire protection

AAC is inorganic and totally incombustible, providing approximately twice the fire protection of normal concrete (Bohnemann, 1993). Also, the geometrical conditions of a prestressed section permits a larger cover of AAC than in an unstressed case, which enhances the measure of fire protection. The two concretes are well known for their high durability records, under most environmental conditions. In this case the durability is improved by the choice of a high quality concrete (K60) and a medium density AAC. Prestressing implies crack-free sections up to the service load level, which protects the members from intruding gases or chemicals and supports durability.
5. Building components

5.1 Number of block sizes

Limited number of basic products (blocks), unlimited number of finished products (hybrid building members)

One purpose of the hybrid system is to reduce drastically the number of block sizes, in order to rationalize storage. Storing finished members must be avoided altogether. The following 6 block sizes are suggested as a standard output, considering production of wall and floor members. If required, the standard can well be extended with a sub-group of sizes.

For non-standard sizes, it is possible to cut blocks to desired dimensions. The reason for cutting blocks at lengths 630 mm is that they are to be milled later on in the process (tongue and groove) and they will then reach 600 mm.

Considering work environment restrictions, confirmed in an annex to the preliminary European standard, prEN 1996-1-1, any block weight should be restricted to 12 kg with the exception of blocks for foundation structures (for which AAC is rarely used). Or block-laying should be mechanized by using crane lifts. In this case only the restriction is applied but very likely a mechanisation will take place with time, connected to production of larger block sizes.

- 6 standard AAC blocks size which is used regularly for production:

<table>
<thead>
<tr>
<th>block</th>
<th>application</th>
<th>width mm</th>
<th>height mm</th>
<th>length mm</th>
<th>weight kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>nr. 1</td>
<td>wall</td>
<td>50</td>
<td>200</td>
<td>600</td>
<td>3.0</td>
</tr>
<tr>
<td>nr. 2</td>
<td>wall</td>
<td>70</td>
<td>250</td>
<td>600</td>
<td>5.3</td>
</tr>
<tr>
<td>nr. 3</td>
<td>wall + floor</td>
<td>100</td>
<td>300</td>
<td>630</td>
<td>9.5</td>
</tr>
<tr>
<td>nr. 4</td>
<td>wall + floor</td>
<td>150</td>
<td>250</td>
<td>630</td>
<td>11.8</td>
</tr>
<tr>
<td>nr. 5</td>
<td>wall + floor</td>
<td>200</td>
<td>200</td>
<td>630</td>
<td>12.6</td>
</tr>
<tr>
<td>nr. 6</td>
<td>wall</td>
<td>400</td>
<td>100</td>
<td>600</td>
<td>12.0</td>
</tr>
</tbody>
</table>

- correction to exact lengths of individual members are made by combining different size blocks and/or sawing the end block(s). The nominal length is reduced by 10 mm at each end.
5.2. Floor (deck) members
All floor members are designed to suit the purpose of building a floor in each individual case. The choice between different total heights as a function of span is a matter of practical consideration. Only over 7.5 m is 300 mm height required.

Since the depth of the layer on top of AAC is only 15-25 mm, it is recommended that the max aggregate size in the concrete be restricted to 4 - 6 mm, which is also the practical limit for walls. It is always true that aggregates should be as large as possible to reduce shrinkage. The design process is outlined in Hellers, 1993.

![Fig. 5.1. Floor deck member of AAC blocks with concrete under prestressing](image)

5.3 Wall members
Walls can be built with AAC in a traditional manner, as masonry. This requires a good mason, who can handle the relatively large blocks on thin bed joints (1 – 3 mm). Comparing with bricks, it implies a far better productivity. See drawings 2:3, 2:4.

The production of hybrid wall members is an easier matter than for floor members. The required manpower is also less. The production contains four steps, placing the blocks with dry joints, milling the channels, prestressing the reinforcement strands and pouring the concrete into the channels. The reason for prestressing is not only to keep the member together but also to increase its capacity, c.f. Aroni, 1967. It is also possible to manufacture a long member, and then cut and divide this structure into smaller wall members.

Prestressing is a way to keep the blocks all compressed over the full contact area, by which the bending stiffness is kept intact, reducing the risk of cracking, especially detrimental to the rendering.
- prefabricated long AAC wall with prestressed vertical reinforcement

Another way of producing a load-bearing vertical capacity is by a long wall principle. This wall is prestressed vertically by strands in the middle of the section. The bending stiffness in the long direction (vertical bending vector) comes from masonry action, stimulated by prestressing pressures.

The AAC-blocks are built into a vertical masonry wall with thin bed joints. The wall stands on a stiff steel frame, which is tilted after the wall is completed. The channels are milled from a horizontal position. Before placing the prestressing strands and grouting the channels, it is particularly important that all dust particles are removed with compressed air or by a vacuum cleaner. The prestressing forces are balanced by a steel profile, which distributes the stresses over the AAC. The channels are filled with HPC and the whole structure vibrated in order to ensure the good bond between strand and concrete.

An alternative is to put all blocks without mortar in dry masonry on a working bed within a surrounding frame. The method is labour saving but unsafe in geometrical precision. The vertical prestressing becomes even more important, as it is the sole force behind the friction, which keeps the wall together in the long direction.

The surface is covered with plaster, and the long wall raised to a vertical position. The wall is equipped with lifting hooks by which the wall can be hoisted on-board a truck for delivery. See drawing 3:25.

**Fig. 5.2.** Prefabricated AAC masonry wall member with prestressed reinforcement and HPC in channels. Non-structural plastering
- Curtain wall
The production of curtain walls follows closely the same process. But the prestressing reinforcement is placed horizontally. Vertical ladder reinforcement is integrated with the top of concrete. After curing the free volumes are filled with high-insulating material (plastic foam), hooked on the ladders. The exterior layer of AAC (50 mm) is glued on the insulation. Then the wall member is ready for rendering.

Fig. 5.3. Prefabricated AAC curtain wall with prestressed reinforcement, HPC concrete, plastic foam insulation, AAC surface layer and rendering
5.4 Lintels

The present manufacturing of lintels over windows and doors of reinforced (non-tensioned) AAC materials is rather complicated. With lintels, the disadvantages of the traditional structural principle are aggravated. Compression is resisted primarily by steel and so are the shear forces. Anchorage is secured by transversal steels and a long support length at each end. It is the product, where the replacement with prestressing technology is most convincing (Nygren, 2002).

A production of prestressed hybrid lintels can effectively rationalize the function of spanning smaller and larger openings. Two kinds of lintels are shown here. The first one is applicable on door lintels of up to 1.2 m (plus 0.15 + 0.15 m for support). It has a symmetrical section of extreme simplicity, a milled channel in the middle, with a prestressing strand at the bottom of a ”T” embedded in AAC. The prestressed concrete can normally resist appearing shear forces without extra steel.

The second option is to pour concrete on one side of AAC-blocks in a clamping geometry and complete a lintel by prestressed reinforcement combined with non-tensioned reinforcement. Large shear forces require diagonal bars, most conveniently arranged by mesh reinforcement.

This form is suitable for window lintels up to 3 m (plus 0.3 + 0.3 m for support). Such lintels must be able to carry floor members of 9 m span, and a maximum variable load of 5.5 kN/m². With a height of 300 mm the span to depth relation is up to 10 and the bending moment and shear forces can be accommodated with reasonably limited deformation.

Such window lintels are skew hybrids with the shear centre of the cross section approximately below the centre of the support. Using an asymmetrical section in this way more or less prevents twisting moments and torsional deformation. This quality needs thorough calculation in each case, which is outlined in Hellers & Lundvall, 1992 and Hellers, 1993.

Since the layer of HPC belonging to a window lintel has a much larger geometry than with other hybrid members, typically 50 mm, the concrete is assumed different and the maximum aggregate size is taken 16 mm.
**Fig. 5.4.** Door lintel of AAC blocks with concrete pour for anchorage and compression

**Fig. 5.5.** Window lintel member of AAC blocks with HPC and prestressed reinforcement bar at the bottom.
6. Production process (Conceptual)

The production process is divided into two stages, the first with only blocks (mass producing industry), the second with a combination of blocks, prestressing and concrete grout into a hybrid of AAC and HPC (finished product industry). These stages, or manufacturing processes, can be located in close combination or geographically apart, depending on market circumstances.

Fig. 6.1. Separated production process of AAC blocks and AAC construction members
Reference: "Lättbetong handbok" 1993

6.1. Facilities of production, machinery and circulating gear

Two options for producing hybrids are suggested in the context:

- Production of hybrids on a long prestressing bed

It is possible to make hybrids of a substantial length on a prestressing bed, a length to be cut down into pieces according to customer ordered size. This is due especially for the production of wall members. Such production can be realized e.g. on the present hollow-core beds, which are normally 100 – 110 m long. Such beds have a width of 1.2 m, which would require an arrangement with masonry of the block sizes suggested in chapter 5. In such a case, the extra investment capital would be comparatively low.
Fig. 6.2. Conceptual separated production layout for an alternative AAC hybrid production plant.
A new production method, with a sequence of operations leading up to the finished product, is suggested in this thesis. Each hybrid member is produced separately, on a production tray. The tray moves on a production line. The operations are conducted by relatively simple methods and machinery. The following conditions have been considered in the design of the production layout:

1- The machinery must be simple to run and maintain. It should be cost effective.
2- Under suitable climate conditions, and project scale, a site production is recommended.
3- The trays must be durable and reusable for a long time in production. They can be made of plywood, metal or other suitable material.
4- In order to rationalize production, a two shift procedure is worth considering.

The necessary manpower in the process has been analysed by the engineer Rolf Bergdahl through correspondence (1994-97), whose estimates have been slightly revised over time.

The different steps in the production process are as follows:

Step 1- AAC blocks are shipped from a parent factory or from a store for blocks to the site of the hybrid production on standard pallets. Blocks are lifted and placed dry on a production tray by a vacuum lift (or by manual means). Then some stabilizing equipment is added in order to prevent any movement of the individual blocks on the tray, (manpower: 1 worker).

Step 2- The tray is sent to the next station, where the channels are milled. The channels are in fact sawn to appropriate width and depth. The width, 30 mm, is decided to accommodate the smallest vibrating poker on the market, which is 28 mm. Surfaces and channels are cleaned from dust particles by compressed air or vacuum treatment. The cleaning is critical to the bond between AAC and HPC, (manpower: 0.5 worker).

Step 3- The prestressing strands are placed precisely in the milled channels. Stiff metal supports for transmitting the prestressing forces onto AAC are mounted at each end. Locks around the strands are mounted. The strands are prestressed to assigned level, (manpower: 1.5 workers).

Step 4- The moisture ratio of AAC is critical to the bond capacity between AAC and HPC. Therefore, it should be measured and adjusted by spraying prior to pouring the concrete. HPC is pumped out through hoses into the channels dragging the tube along the strand in order to secure the bond between steel and HPC. Filling the channels is a first step of the concreting. Mounting side forms on the AAC bed and a metal mesh between the forms, which is designed to resist upcoming tensile forces from prestressing finishes the preparation for the final concreting, (manpower: 1 worker).

Step 5- The HPC concrete is poured onto the AAC bed (second part of pouring the concrete). The thickness of this layer is between 15 and 25 mm. After concreting, the tray is transported to a vibration table for a finishing treatment of the composite. This last step is perhaps not necessary, when production procedures have stabilized, but is
included here to secure the bond between materials. The preparation of the concrete itself is an adjacent procedure, (manpower: 1 worker).

Step 6- Now, the purpose is to move the tray to a curing chamber. The member is mounted in a rack by use of a lifting table. In the chamber, the temperature is between 70 and 80°C. The minimum required curing time is about 6 h. The curing chamber should be checked regularly, (manpower: 0.5 worker).

Step 7- After curing the hybrid is strong enough to resist all stresses. The tray and formwork can be removed, cleaned and sent back to the starting point to complete the 24 h cycle, (manpower: 0.5 worker).

Step 8- The hybrid member is sent to milling on both sides by a special machine (note that the material is now cured and strong). The milling should be conducted according to drawing, either as floor or wall member. Both sides of the member are then cleaned from dust particles, either by compressed air blowing or vacuum treatment, (manpower: 0.5 worker).

Step 9- The hybrid member is now moved to temporary storage or delivered directly to the building site, (manpower: 0.5 worker + 1 supervisor).

The table below shows how much manpower per skift is needed to run the entire process:

<table>
<thead>
<tr>
<th>nr.</th>
<th>time minutes</th>
<th>number of persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>step 1</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>step 2</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>step 3</td>
<td>6</td>
<td>1.5</td>
</tr>
<tr>
<td>step 4</td>
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<td>1</td>
</tr>
<tr>
<td>step 5</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>step 6</td>
<td>6</td>
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<tr>
<td>step 7</td>
<td>360</td>
<td>0.5</td>
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<tr>
<td>step 8</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>step 9</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>supervisor</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

With a characteristic sequence of 6 min, it is possible to produce 10 members/h. The average area of such members is estimated at 5 m², which leads to a production rate of maximum 400 m²/d.shift. A one shift procedure implies a production of 100,000 m²/an, or with an average member depth of 0.25 m, 25,000 m³/an. By doubling to a two shift procedure, this figure is doubled to 50,000 m³/an. This is one fifth of the average volume produced by a modern AAC plant (250,000 m³/an), c.f. chapter 2.

A single family house requires some 50 m³ AAC. So, a one shift production corresponds to 500 such houses per year.
6.2 Extension of a basic block production or establishing a location on a building site

The choice between a permanent extension of a basic block production or a temporary site is a matter of several questions:

- is the project in question large enough to carry the initial costs of a temporary site production?
- is it possible to establish a quality control system of sufficient credibility?
- is manpower available and under what conditions?
- what happens when the project is finished?

Experience will tell how to handle these questions. It is critical to understand that blunders will not be excused on the market – everything must be made to quality requirements.

6.3 Production in two categories – one in general and one high-tech version

- The general category of AAC hybrids has no extra insulation. It is plain and homogeneous material. It is applicable everywhere, all over the world, being the most economical category to build but not to run, when the cost of heating is considered.

- The more advanced category of AAC hybrids have an extra layer of heat insulation and may also have other features to raise the capacity in different respects. The products may have a finishing exterior layer of AAC, which is supposed to carry the rendering. Such products are suited for advanced markets in the temperate, industrialized zone of the world. They carry a higher price tag but have lower running costs.

6.4 Management of production by CAD/CAM application

Prefabrication within the building industry has developed after WW2. Prefabrication offers a limited number of standardized products, usable for normal buildings. The prefab-industry after 1960 has refined its quality control, developed the hollow-core production into a fully industrialized process, but stayed rather conservative in its output of other products.

Only to-day are the means at hand to modernize the output through a flexible and efficient production, controlled by CAD/CAM, released from the straps of standardization. By flexible form systems, it is possible to make a wide variation of requested products, not necessarily more expensive. The introduction of the present hybrid technology belongs to this trend.

A communication between buyer or the architectural office, the hybrid’s production centre and the building production site can be maintained through Internet and sometimes Intranet. They help to establish the production facility behind a large variety of products, without any major changes of the production process or need for extra resources. The output of products is enriched through new technology.

Any building member is designed in an architectural office and the design is sent by electronic mail to the production plant. After checking in the factory design office, the specifications are sent to the production workshop through Intranet. The number of blocks can be automatically counted and sent from the storage to the production section. Or, the
order can come from another block production plant. Production can begin just in time before the delivery of a hybrid member. In principle, by a good production planning, the need for storage of AAC blocks may be further reduced.

NCC Komplett at Hallstahammar is a new automatic building production facility, based on concrete, which demonstrates the possibilities by “production to order”. The better part of the building members is produced directly in cooperation with an architectural office. The finished members are transported to the building site for assembly (Hindersson, 2006).

- Location of facility for production of hybrids
Utility plants for producing electricity, and sometimes for district heating, are numerous in the world, fuelled normally by coal powder. In Sweden, there are just a few plants of this kind, Stockholm, Västerås, Helsingborg, Malmö. Such power plants generate two by-products in large volume, fly ash (PFA) and excessive heat. In some countries, like Denmark and the Netherlands, the by-products have found adequate use by district heating and mineral production. But in several other countries, these by-products cause severe economical and environmental problems.

If an AAC producing block facility is located near an utility plant, both the by-products may be used efficiently in the process. The heat from the utility holds some 250°C, while the desired temperature in the autoclaving process is 190 – 205°C. The use of PFA in the recipe for making AAC has been outlined in chapter 2.

A next step is to analyse the location of a hybrid member production. If such a facility is also located near an AAC block production and a coal power plant, it is possible to use the heat by-product once more. The desired temperature in feeding the curing chamber facility is 70 – 80°C, which is readily transmitted from the down-side of the autoclaving process. A complex of such three plants can make an efficient industrial conglomerate. Interdependency between industries has not been popular for quite some time, in fact after 1930 when it was considered more advantageous to promote the development of each industry, which should then be free to find its own path on the open market. This pattern might well change under the pressure of future energy efficiency. Recent examples have appeared, e.g. in Denmark.
Fig. 6.3. Industrial conglomerate
The process shows the use of heat as by-product and fly ash for the production of AAC blocks and prestressed hybrid members
7. Application in buildings

7.1 Detailing and specification

Hybrids are recommended, first of all for dwelling houses or apartment houses up to three storeys. But it is quite possible to use hybrid members in general, and in high buildings with steel or concrete frames, which are supplemented with loadbearing roof and floor structures and with curtain walls of a hybrid structure. Including AAC in all enveloping surfaces increases the basic fire resistance, which is a security measure in times of terrorism, when you never know what fire load may hit your building.

Design and planning of the most usual and important building details are shown in this chapter.

Fig. 7.1. Connection between floor deck members, wall members and lintel
7.2 Floor and roof (deck) member

Two extreme designs of the connection between floor/roof members and load-bearing wall are demonstrated:

1- A normal design of a joint contains only one reinforcement bar, the longitudinal tie-bar running horizontally around the total circumference of the building. The horizontal seams between members are filled with concrete, to form a complete floor surface. In regions with limited seismic risk, like in northern Europe, no extra steel is required. See drawings 3:1, 3:3, 3:5, 3:7.
2- A different design of a joint contains extra reinforcement in all directions in order to add ductility and energy absorption capacity to the structure. The horizontal seams between members are reinforced with steel that runs over the joints down between wall members, whose channels are filled with low viscosity concrete. For continuity, vertical steel passes the floor from upper to lower wall. The on-site technology is very sensitive to the quality of all receiving surfaces, which must be thoroughly wetted prior to concreting. Also, the concrete itself must be densely packed, at best vibrated wherever possible. See drawings 3:2, 3:4, 3:6, 3:8.

The following table shows the minimum support length of floor member over wall member and lintel:

<table>
<thead>
<tr>
<th>floor member length</th>
<th>wall member width</th>
<th>the minimum support length of floor member over wall member</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>L &lt; 5.0</td>
<td>200</td>
<td>65</td>
</tr>
<tr>
<td>5.0 ≤ L ≤ 7.5</td>
<td>250</td>
<td>90</td>
</tr>
<tr>
<td>7.5 &lt; L ≤ 9.0</td>
<td>250 - 300</td>
<td>120</td>
</tr>
</tbody>
</table>

The support length is designed to resist the generated contact pressure under full load. See drawing 3:18.

7.3 Walls, openings and gables
A wall member can be placed directly on a concrete slab foundation. Wall members can be assembled with hoisting equipment, such as crane, lift or wall cart. A long channel is milled on both sides of the member in the production process. These channels must be wetted (sprayed with water) before filled with low viscosity concrete.

After the foundation slab has shrunk to a reasonable level (more than three weeks after pouring) the wall members can be placed with the channels pointing towards the inside of the building, side by side in order and the decks of the first floor be mounted. Before placing the tie-bar, all channels between wall members must be filled up to the wall height. See drawings 3:9, 3:10, 3:11, 3:12. Then the tie-bar is placed and the edge block before filling the gap with concrete under vibration to achieve compatibility.

The interior load-bearing wall members should be placed with symmetry in order that the load from the floor is divided evenly over the supporting structure. See drawings 3:13, 3:14.

In regions with seismic activity (according to the UN, more than 80% of the demographic growth in the 21st century will happen in seismic prone regions) all vertical channels and horizontal seams can have steel embedded in order to enhance compatibility, ductility under strong deformation and energy absorption. The steel is placed on-site, as the building is erected. The literature on AAC and seismic conditions has been growing over recent years and it applies naturally to the BCE-technology. The critical condition lies with the preparation of surfaces and with the concrete itself, which must be self compacting and fluent in order to secure the bond between concrete and steel.
Adding heat insulation material to wall members is an option to sharper market requirements for energy efficiency in buildings. See drawings 3:7, 3:8.

7.4 Lintels (over windows and doors)

A hybrid lintel is used over windows and doors. Lintels connect floor members and hold the wall members together. Adjacent wall members are recessed to accommodate the lintel, which must have a full support length on both sides. In an exterior wall of highly insulated members, this requires special members with full AAC measures. Avoiding standardization such members cause no problems, which is an asset of the present BCE-system. In the drawings, several details for engineering of door and window lintels into the building system are shown. See drawing 3:16.

Under seismic conditions, lintels must be connected to floor and wall members by extra strengthening reinforcement bars. See drawing 3:17.

The following table shows the minimum support lengths of lintels placed on wall members. The support lengths, which are from 150 to 300 mm, are designed to resist the contact pressures.

<table>
<thead>
<tr>
<th>wall opening mm</th>
<th>the minimum support length of lintel over wall member mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L \leq 1800$</td>
<td>150</td>
</tr>
<tr>
<td>$1800 &lt; L \leq 3000$</td>
<td>300</td>
</tr>
</tbody>
</table>

The minimum support length of lintel over wall member is 150 mm. The maximum wall opening is 3 m and the support length is 300 mm.
7.5 Reinforcement strengthening to comply with seismic conditions, ductility

A new combination of a masonry wall of AAC blocks and floor members is suggested in this connection, designed for better energy absorption. Holes are drilled down into the AAC blocks and steel bars coming from horizontal seams between floor members, bent over the joints, end at the bottom of these holes. The same procedure is possible with lintels, which can be strengthened to better unity of the entire structure. See drawings 3:19, 3:20, 3:21. The equivalent design is applicable with load bearing gables, which are most productive in creating a stiff-box behaviour under seismic load. See drawings 3:22, 3:23, 3:24.

Fig. 7.3. Connection between floor deck members and AAC masonry wall with continuity reinforcement bar
(Extra reinforcement is recommended for seismic regions)
8. Conclusion, influence of BCE on the AAC technology and on the concrete prefab technology

AAC is a global material, whose composition requires raw materials which are available in abundance practically everywhere. The production of AAC has expanded rapidly over recent years. The perspective for further growth is good. AAC has the capacity to take over a larger market share on a global scale from other materials for the following reasons:

- AAC can make use of by-products from other industries, like fly ash and excessive heat
- AAC can be produced large scale in automated block factories in just a few (6) sizes
- AAC can be converted into full-value members of a building system by use of the BCE-technology

Hybrids of AAC/HPC have the potential to create new applications for AAC, and increase the AAC production. New AAC block plants will emerge as a consequence.

This thesis presents a new production system for different building members. The BCE production system is an answer to many of the requirements of new industrial and ecological demands. This system is more flexible than other production systems for producing building members, because of a low investment level combined with efficiency. It can be applied under almost any climate conditions and in different types of building, up to three storeys with AAC only, in larger buildings using combinations with stronger materials in frames.

A hybrid is a combination of closely related but different, reliable and approved building materials, in our case AAC, HPC and prestressing strands. All of these have proven reliability and durable function, individually and in combinations. The purpose of a hybrid technology is to make use of individual properties in such a way that the sum exceeds the parts. Natural resources are conserved.

In the studies behind the present dissertation, several production methods and systems have been reviewed. The conceptual production layout is thought to be optimal under the circumstances, uncomplicated and carrying a low investment requirement for a pilot plant. There are other solutions available for more automated production systems, which may come into question in the future.

The most important and frequently applied details are designed and shown in the thesis. Such details can be performed on site. The members can be readily assembled by semi-skilled manpower from the building sector.

In the process of developing the BCE technology, some industrial production of hybrid lintels has been conducted by Ytong in Sweden (2002). This test production did not proceed into building members. The result was convincing, reflecting the conviction by leading Ytong representatives (Nygren, 2001) that the prestressed hybrid technology would be especially advantageous with lintels for which the awkward unstressed reinforcement might be considerably simplified and economized.
The next step in developing the BCE technology would be to investigate weak points after consulting the adequate industry. It is likely that the shear stress between AAC and HPC will have to be analysed further, which requires FEM technique. The purpose of such a step would be to reveal limits for coordination over joints within and between structural members. It is a way of checking the validity of earlier approximations.

Also, it would be highly interesting to elaborate combinations of members in building systems, taking advantage of the freedom to form single members with little restrictions other than length. Or try new shear-wall systems, where the capacity would rely on prestressing of horizontal joints.
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Part 2

Drawings of structural members

Prestressed hybrids of AAC and HPC
SECTION
SIDE CONNECTION BETWEEN FLOOR MEMBERS (200 mm)
SECTION
SIDE CONNECTION BETWEEN FLOOR MEMBERS (300 mm)
SECTION
SIDE CONNECTION BETWEEN WALL MEMBERS
SECTION
EXTERIOR BEARING WALL MEMBER WITH INSULATION

\[ U_p = 0.135 \text{ W/m}^2 \text{ °C} \]
GRAVEL SIZE:
WINDOW LINTEL: max 16 mm
DOOR LINTEL: max 4 mm
Part 3

Drawings of application in buildings

Prestressed hybrids of AAC and HPC
SECTION
CONNECTION BETWEEN EXTERIOR BEARING WALL, VERTICAL WALL MEMBERS TO FOUNDATION SLAB
SECTION
CONNECTION BETWEEN EXTERIOR BEARING WALL, VERTICAL WALL MEMBERS TO FOUNDATION SLAB
(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)
SECTION
CONNECTION BETWEEN EXTERIOR BEARING WALL MEMBER
TO FLOOR MEMBER

<table>
<thead>
<tr>
<th>FLOOR MEMBER’S SPAN (m)</th>
<th>WALL MEMBER’S WIDTH mm</th>
<th>THE MINIMUM SUPPORT LENGTH OF FLOOR MEMBER OVER WALL MEMBER mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>L &lt; 5</td>
<td>200</td>
<td>65</td>
</tr>
<tr>
<td>5.0 ≤ L ≤ 7.5</td>
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<tr>
<td>7.5 &lt; L ≤ 9.0</td>
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CONNECTION BETWEEN EXTERIOR BEARING WALL MEMBER TO FLOOR MEMBER
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SECTION
CONNECTION BETWEEN INTERIOR BEARING WALL, VERTICAL WALL MEMBERS TO HORIZONTAL MEMBERS

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3:5
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(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)

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<td>250 - 300</td>
<td>120</td>
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WALL

\[ q_e = 150 \text{ kg/m}^2 \]
\[ U_p = 0.15 \text{ W/m}^2\text{°C} \]
\[ R_w^1 = 44 \text{ dB} \]

SECTION
CONNECTION BETWEEN EXTERIOR BEARING WALL MEMBER TO FLOOR MEMBER WITH INSULATION

<table>
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<th>FLOOR MEMBER'S SPAN (m)</th>
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<tr>
<td>7.5 &lt; L \leq 9.0</td>
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<td>120</td>
</tr>
</tbody>
</table>
WALL

- $a_e = 150 \text{ kg/m}^2$
- $U_p = 0.15 \text{ W/m}^2\text{°C}$
- $R_w^1 = 44 \text{ dB}$

SECTION

CONNECTION BETWEEN EXTERIOR BEARING WALL MEMBER TO FLOOR MEMBER WITH INSULATION

<table>
<thead>
<tr>
<th>FLOOR MEMBER'S SPAN (m)</th>
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PLAN
EXTERIOR BEARING WALL OF VERTICAL WALL MEMBERS,
CONNECTION IN CORNER, TIE STEEL BARS
PLAN
EXTERIOR BEARING WALL OF VERTICAL WALL MEMBERS,
CONNECTION IN CORNER, TIE STEEL BARS
(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)
PLAN
CONNECTION BETWEEN EXTERIOR WALL MEMBERS
AND INTERIOR WALL OF AAC
PLAN
CONNECTION BETWEEN EXTERIOR WALL MEMBERS
AND INTERIOR WALL OF AAC
(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)
PLAN
SIDE CONNECTION BETWEEN INTERIOR BEARING WALL MEMBERS,
VERTICAL WALL MEMBERS TO HORIZONTAL MEMBERS
PLAN
SIDE CONNECTION BETWEEN INTERIOR BEARING WALL MEMBERS,
VERTICAL WALL MEMBERS TO HORIZONTAL MEMBERS
(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)
ELEVATION
CONNECTION OF FLOOR MEMBERS TO WINDOW LINTEL
SECTION
CONNECTION BETWEEN EXTERIOR BEARING WALL MEMBER TO FLOOR MEMBER AND WINDOW LINTEL

<table>
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<tr>
<th>WINDOW SPAN mm</th>
<th>THE MINIMUM SUPPORT LENGTH OF LINTEL OVER WALL MEMBER mm</th>
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<tbody>
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SECTION
CONNECTION BETWEEN EXTERIOR BEARING WALL MEMBER TO FLOOR MEMBER AND WINDOW LINTEL
(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)

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SECTION
CONNECTION BETWEEN FLOOR MEMBER AND WINDOW LINTEL
THE MINIMUM SUPPORT LENGTH OF LINTEL OVER WALL MEMBER
SECTION
CONNECTION BETWEEN FLOOR MEMBER AND AAC MASONRY WALL WITH CONTINUITY BAR
(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)

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SECTION
CONNECTION BETWEEN FLOOR MEMBER AND AAC MASONRY WALL WITH CONTINUITY BAR
(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)
VIEW
CONNECTION BETWEEN FLOOR MEMBER AND THE WALL OF AAC BLOCKS WITH CONTINUITY BAR
SECTION
THE ROOF RIDGE
CONNECTION BETWEEN FLOOR MEMBER, ROOF MEMBER
AND AAC MASONRY WALL WITH CONTINUITY BAR
(EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)
SECTION
CONNECTION BETWEEN WALL MEMBER,
FLOOR MEMBER AND ROOF MEMBER
SECTION OF ROOF RIDGE CONNECTION BETWEEN FLOOR MEMBERS AND AAC MASONRY WALL WITH CONTINUITY BAR (EXTRA REINFORCEMENT IS RECOMMENDED FOR SEISMIC REGIONS)
VIEW
PREFABRICATED AAC MASONRY WALL MEMBER
WITH PRESTRESSED REINFORCEMENT BAR AND
HPC CONCRETE