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Swiss Locomotiv and Machine Works
CH-8401 Winterthur, Switzerland

Lightweight design in modern locomotive construction

The driver's cab of the new
„Locomotive 2000" – Re 4/4 460 – made of fibre reinforced plastic

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Front cover: Front of driver's cab of Lokomotive 2000, made of fibre reinforced plastic (Photo: by Saurer, Arbon).

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Lightweight design in modern locomotive construction

"Light Nose for Fast Locomotives"

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From steel to plastic: the driver's cab of the new Locomotive 2000 Series 460 is made of fibre reinforced plastic

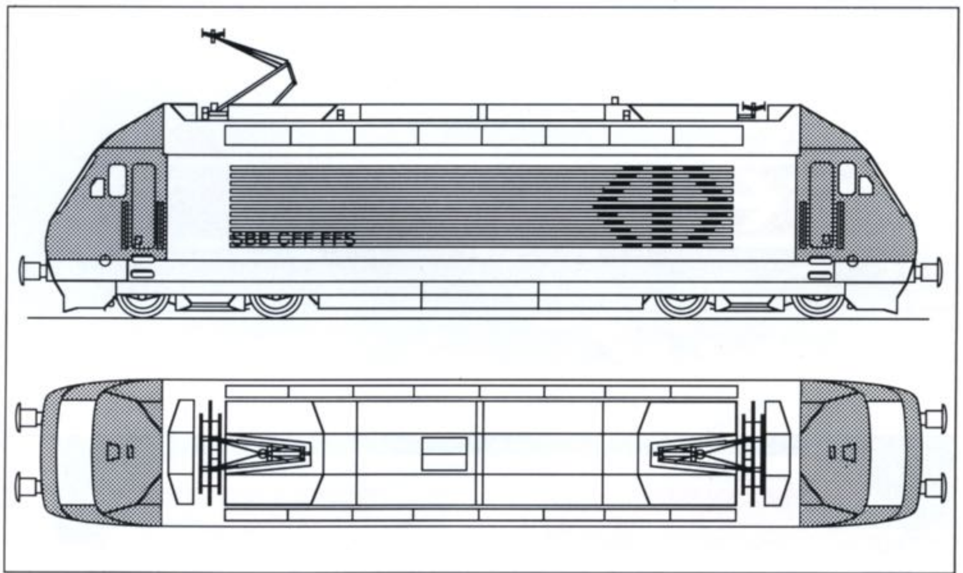
Until very recently locomotives have always been made of steel. Fibre reinforced plastic (FRP) has been used on occasions in some individual subordinate components which do not have high strength requirements, such as casings or machine room doors, but the use of fibre reinforced plastics in load bearing components for rail vehicles appeared to be out of the question. Yet the stress bearing capacity of plastic has been proved in aircraft construction years ago. Everyone knows that aircraft have to be light, because they need to fly, but in reality they are twice as heavy as locomotives.

Locomotives must not exceed prescribed axle loads, but in the age of the high speed train, locomotives have to be increasingly powerful, so that the electrical equipment becomes increasingly heavy. To compensate for this, weight must be saved elsewhere in the mechanical parts. Lightweight construction is therefore an important objective for the engineers at the Swiss Locomotive and Machine Works (SLM) in Winterthur.

In the case of the new locomotive of the Swiss Federal Railways, the Locomotive 2000, there was, in addition to weight reduction, a further criterion which was decisive in the selection of fibre reinforced plastic for the construction of the driver's cab.

With the high speeds at which trains now travel, aerodynamics have come to be not only an influence on energy consumption, but also an important factor in relation to the safety of man and machine. With this in mind, the internationally famous Italian designer, Pininfarina, was asked to assist in producing a design which optimised the aerodynamics of the body of the locomotive, and at the same time produced a style for the future and took into consideration the requirement for a multipurpose locomotive. This close co-operation resulted in a modern locomotive with a spheroidic cab design.

Previous locomotives were designed to be made of metal, so the silhouettes were mostly angular, and the surfaces were mainly flat or at most curved cylindrically.

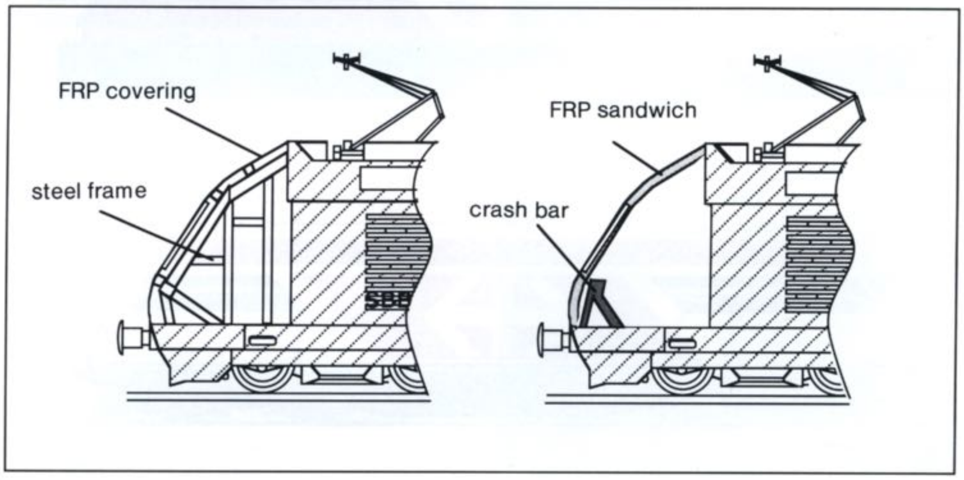


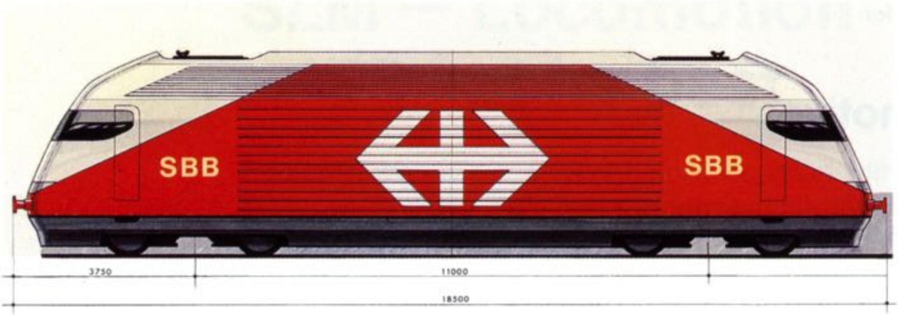
Type sketch of the Locomotive 2000 with the two superimposed driver's cabs made of plastic (Drawing SLM).

However metal can only be used for the new three-dimensional curves with a disproportionate degree of technical effort and a large amount of manual work. It would be completely uneconomic to use a metal press to produce the spherically bent sheet metal parts in the restrictive numbers required, particularly as they are very thick compared with those used in the automobile industry.

When two highspeed trains pass each other, high pressure shockwaves are created. The-

Two possible solutions to the driver's cab design: left, the steel frame with a covering of fibre reinforced plastic and right, the self-supporting FRP sandwich construction with a crash bar integrated into the driver's console. The latter was the one used (Drawing SLM).

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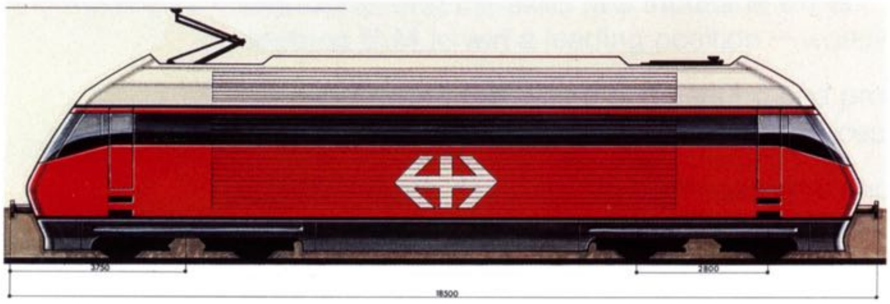
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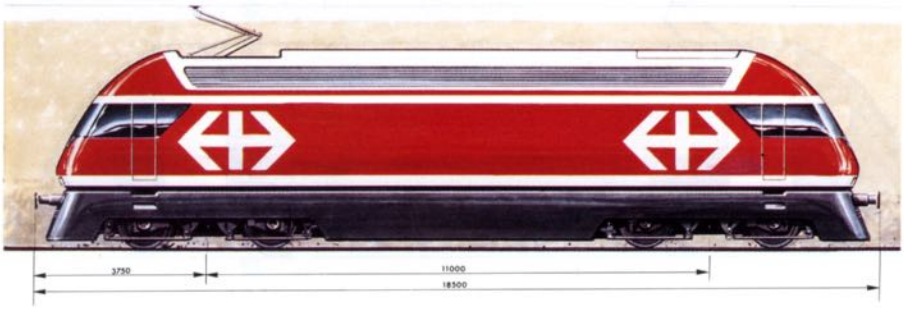
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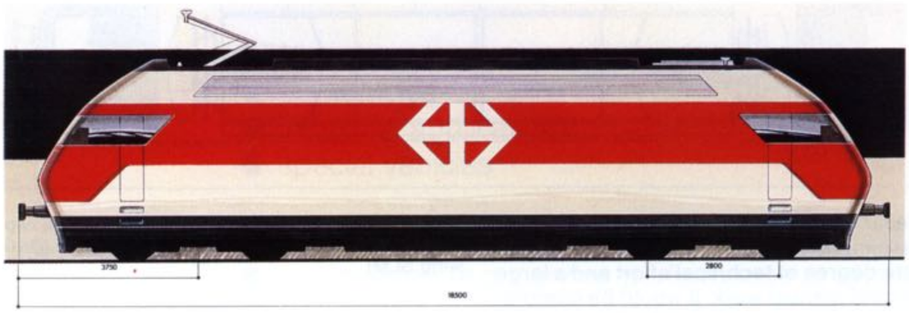
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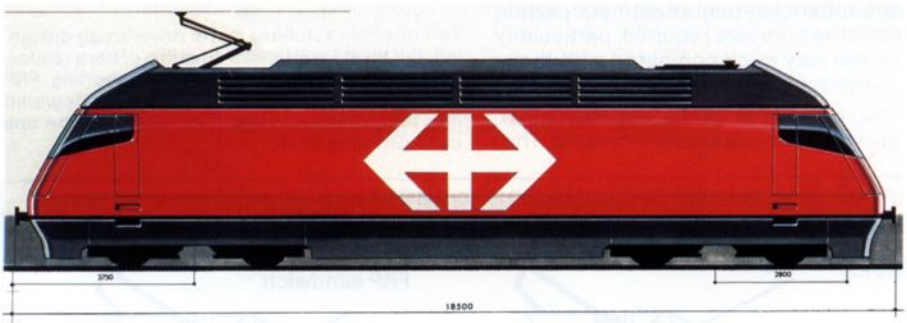
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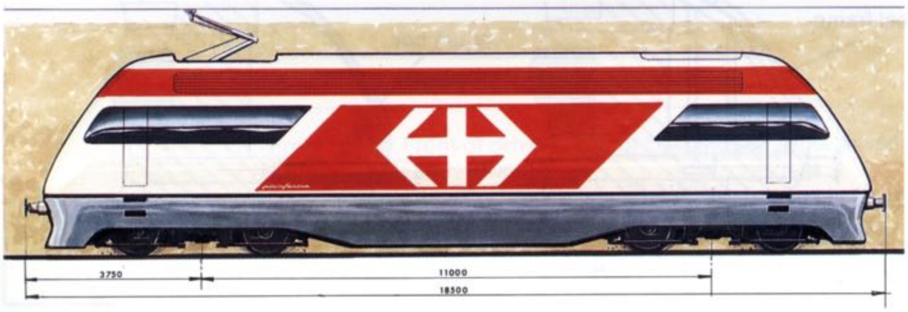
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Right: Mounting the FRP driver's cab as a prefabricated module onto the steel locomotive body during assembly (Photo SLM).

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A selection of the Pininfarina design studies. The fourth proposal was chosen after extensive wind tunnel tests (SLM/SBB).

se shockwaves are particularly complex and dangerous in tunnels and at the same time tunnels are becoming more and more common. For this reason, the driver's cab is not only aerodynamically designed but also pressurised to protect the engine driver from pressure changes within the cabin. The windows, doors, hatches and other components must therefore fit with the maximum precision. Excellent reproducibility of the cabin's dimensions is essential to achieve this exact fit in multiple production. Experiments using conventional metal construction showed that, without making considerable concessions to the cabin's aesthetics, this accurate fit could only be obtained with an excessive amount of work to properly align the welded sheets and the supporting metal frame.

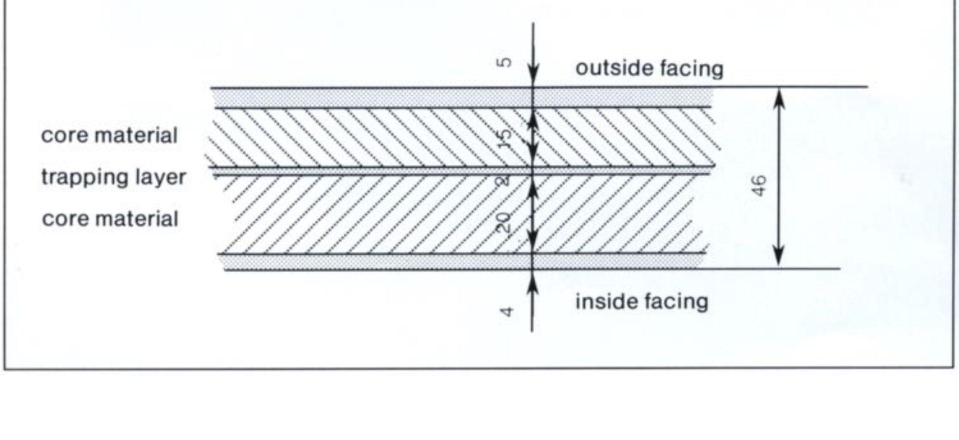
Comparing the various design and construction possibilities, it became clear that using fibre reinforced plastic will achieve the necessary reproducibility of the spherical front of the locomotive in multiple production, and that at the same time would also give the required reduction in weight.

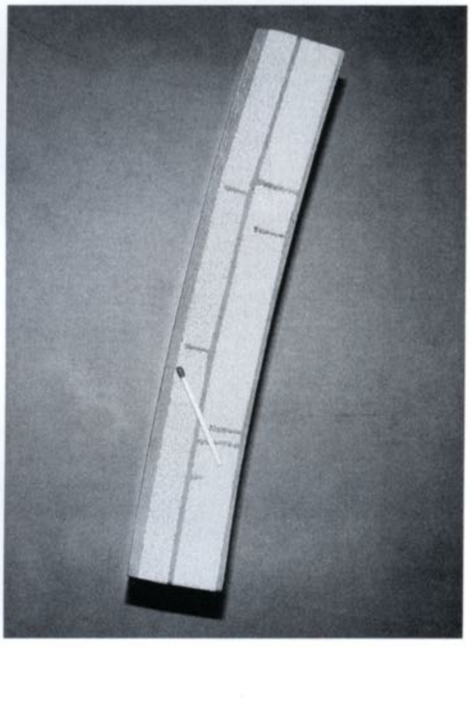
Production in fibre reinforced plastic in the dimensions required needs profound specialist knowledge and great practical experience. Therefore several specialist companies were asked for help. After a preliminary evaluation, two versions of the construction were shortlisted:

One of them, a conventional form of construction, consisted of a simple steel frame with a superimposed plastic covering made of glass fibre reinforced plastic laminate. The other was a self-supporting sandwich structure. The version with the plastic covering soon had to be eliminated for the following reasons:

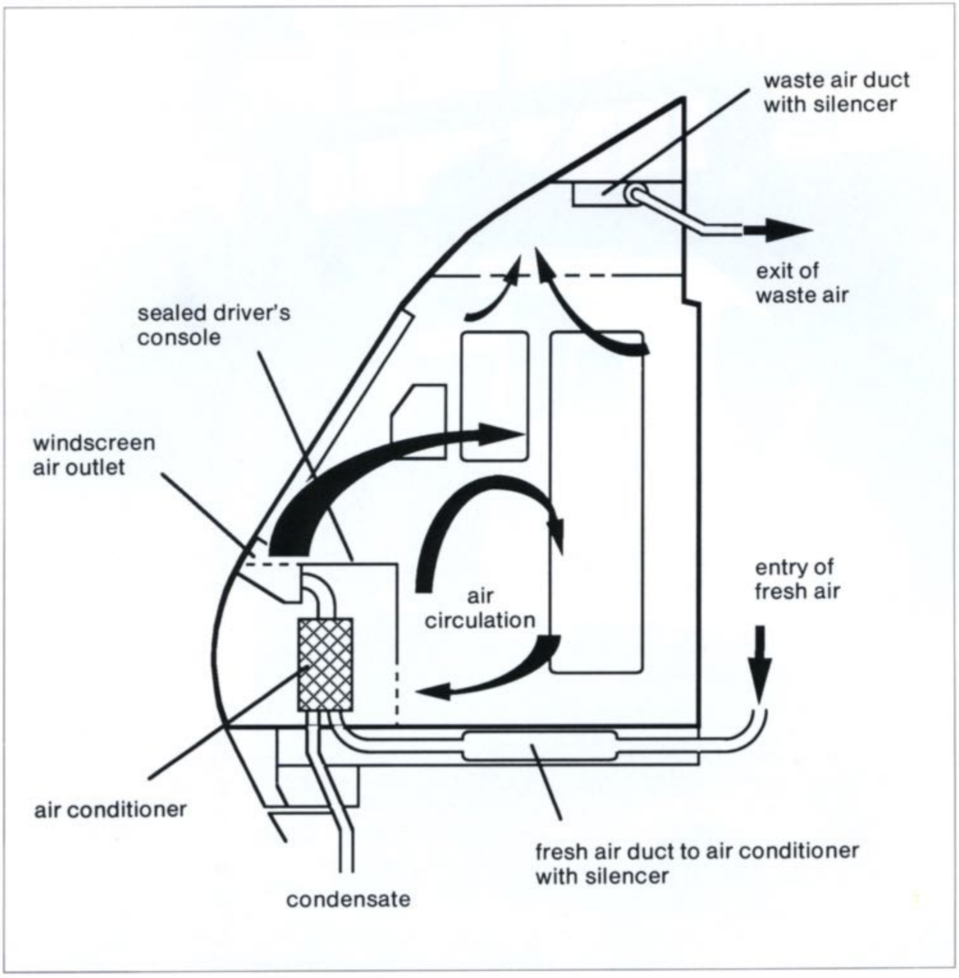
- Hardly any saving in weight could be achieved.
- Problems were foreseen over inserting the windows, mirrors and other parts flush with the necessary precision.
- A lack of rigidity was expected to cause difficulties when trains cross in a tunnel causing large external deviations of pressure to arise. Even with the pressure resistant version of the cab, the pressure deviations were likely to be transmitted into the interior of the cab due to the "pumping effect".
- The resistance to penetration by small impacting objects was low, and additional protection would have been necessary.
- As with steel, additional thermal and sound insulation and an inner jacket would have been required.

Thus the FRP sandwich design for the front of the locomotive was selected. It provides an integral solution to all the essential problems, with a cab module that is astonishingly easy for the locomotive builder to install and a weight saving of about 1000 kg per locomoti-





Section through the sandwich construction, showing the outside and inside facings, two layers of core material and the intermediate or trapping layer in the middle. The weight of the sandwich construction (46 mm thick) corresponds approximately to the weight of the 2 mm of steel which has usually been used up to now, and at the same time the heavy steel frame is dispensed with. (Photo and drawing: Saurer).



ve. This reduction in weight was very welcome given that electrical equipment providing the very high performance of 6100 kW had to be installed. The most important features of this form of construction are described in more detail below.

Left: The air paths and the air-conditioning principles used in the driver's cab. The driver's cab is pressure tight with a large sloping front window and this makes it necessary to have a high performance air-conditioning unit. The air-conditioning for the driver's cab is integrated into the ventilation system of the locomotive. Fresh air is drawn in at the roof tilts through filters. The aerodynamic design of the spherical front of the locomotive ensures that the air flow does not break away at the transition of the forefront to the roof but even at high speeds will return again to the roof surface close after the roof-edge. Thus constant air supply is guaranteed to the roof space, which in its entirety is designed to calm down the air turbulences. From there the air is fed to the engines and the driver's cab. In order to compensate for sudden deviations in pressure, the driver's cab is ventilated by a high pressure feed and the exhaust ventilators have quick closing shutters. As the selected sandwich structure has a thermal insulation coefficient of about 0.75 W/m²K additional thermal insulation of the cab walls is not necessary (Drawing SBB).

Below: A locomotive of the 460 series under construction. The modular cab units are clearly visible (Photo SLM).

The complicated shape of the driver's cab is reproduced in composite plastic materials and not in steel plate for reasons of weight and ease of production (Photo SLM).

Sandwich Construction

Sandwich structures consist of an outside and an inside facing and a light core in the middle. Such structures are especially rigid and light. In the case of the Locomotive 2000, an asymmetric set up of the facings was selected, with both the outside and inside facings being made of glass fibre reinforced modified polyester resin but of different thicknesses. The decisive point was the selection of the construction of the textile fabrics for the reinforcement of the facings.

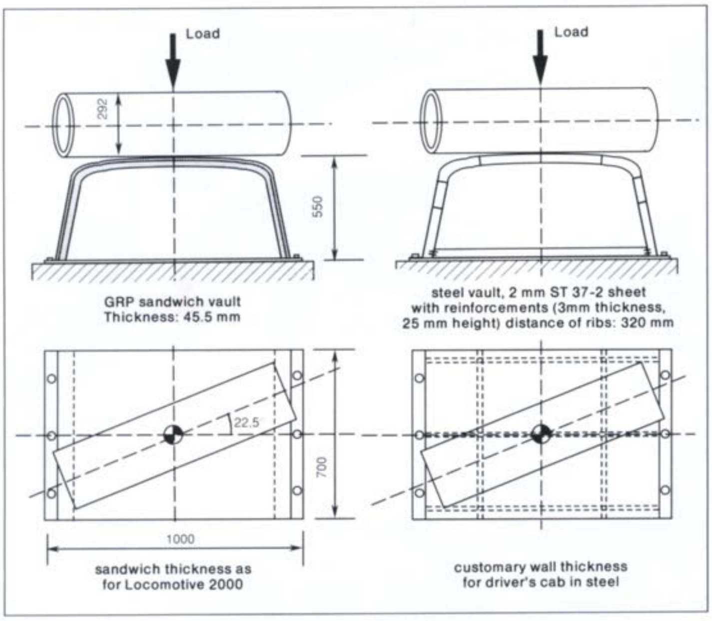
Core Material

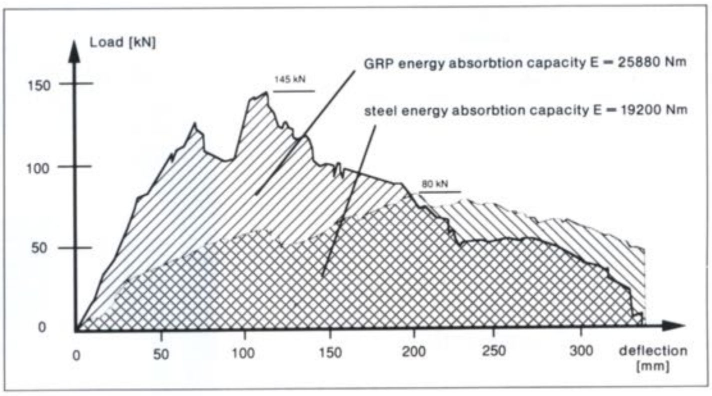
A tough rigid damage tolerant linear PVC foam proved to be the suitable core material. Honeycomb structures, polyurethene foams or cross-linked PVC foams were eliminated as core materials because although they are very stiff and strong they are brittle.

A tough core material is also required because temperature differences will cause it to expand to a considerable extent (Temperature differences between the inside and the outside of up to 80 degrees centigrade are to be expected in very hot weather, particularly as parts of the outer coating of the locomotive are dark in colour.)

Between the foam cores there is a fibre reinforced trapping layer wich considerably increases the resistance to penetration. This intermediate layer is also made of glass fibre reinforced polyester. Glass proved to be the most suitable fibrous material as it has relatively low stiffness (low modulus of elasticity) combined with high strength in conjunction

Examples of the Locomotive 2000 under construction: on the right the body with the plastic driver's cab primed in white and on the left the finished painted locomotive body (Photo A. Staub 19.6. 1990).





Left: Experimental apparatus to measure the ability to absorb energy. A press applies high pressure to cylinders made of plastic (left) and of steel (right) (Drawing SLM).

Above: Load/deflection diagram showing the results of the experiment to measure energy absorption. It shows the way in which steel deforms under pressure (as is well known) and the surprising resistance to deformation demonstrated by the sandwich component. The shaded area shows the energy absorbed in the respective case. The components were compressed to up to 38 % of their original height (Drawing SLM).

with high elongation at break. Glass fibre reinforced polyester is also inexpensive, long lasting and can be easily worked both in production and repairs. Polyester's well known problem of shrinking must of course be taken into account both when making models or moulds and during production.

Impact Test

Impact tests were carried out using the sandwich constructions shown in the illustrations and repeated with variations of them. For this purpose respective sandwich panels (measuring approximately 80 cm x 80 cm) were impacted with a UIC testing body weighing 1 kg. The sandwich construction being described is resistant to an impact speed of at least 280 kmph. As expected a similar but more rigid construction demonstrated a less good result. Simple technical modifications can increase the resistance to penetration to at least 315 kmph. In the case of all the samples with tough elastic cores, the damage remained very localized, and even when the sample was actually pierced, the hole barely exceeded the diameter of the projectile. However when a rigid core material was used, a large area of the sandwich panel was destroyed as a result of shear failure of the core material.

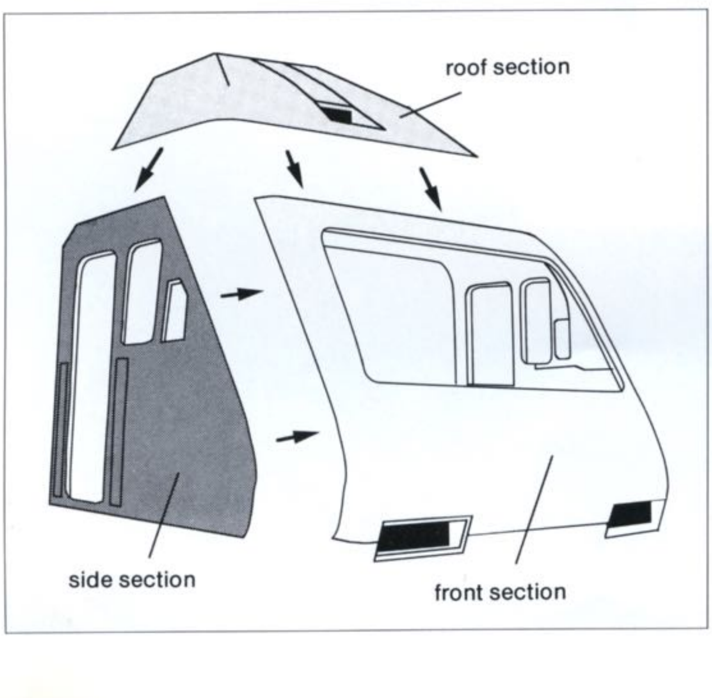
Energy Absorption

Empirical experiments were carried out to provide information about the behaviour of sandwich constructions as compared with steel constructions in the event of a crash. Two structures were produced, one in plastic and the other in steel, each in the form of a vault, and both were compressed to 38 % of their original height by means of a press. The wall thicknesses and the construction of the two samples were the same as that of the respective driver's cabs. As the diagram shows, the energy-absorbing capacity of the sandwich GRP construction with its linear foam core compared favourably with the steel construction.

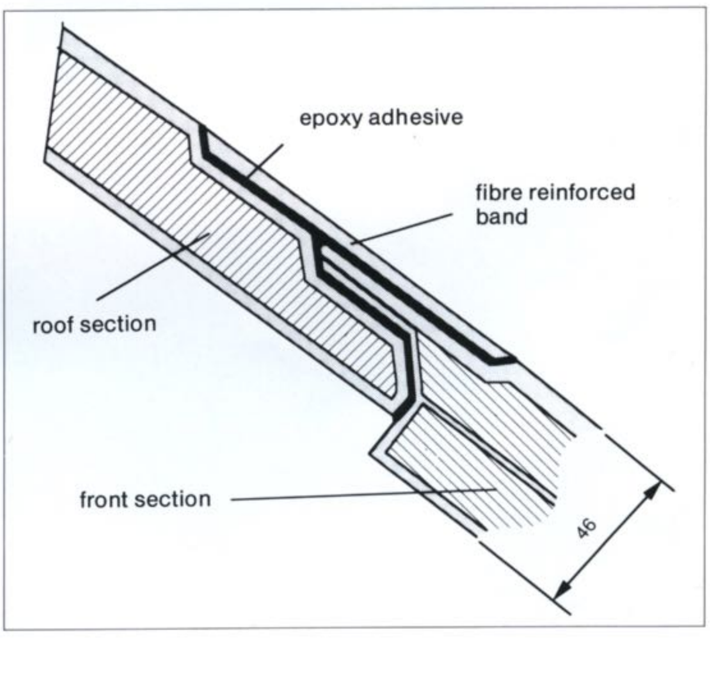
Fire Tests

Plastics, being by their nature organic materials, are flammable. Adding fire retardant additives however can greatly reduce the level

The GRP driver's cab is produced in four individual sections: the roof, the front, and two side panels (Drawing Saurer).



Schematic diagramm showing the joint of the roof and front section (Drawing Saurer).



The finished locomotive 2000 on the track to the Gotthard near Melide. The external view gives no clue that it is made partly of plastic and partly of steel (Photo F. Suter 10.11.1991).

of flammability. Use was made of this in the selection of the materials to be used in the Locomotive 2000. Tests carried out by the Experimental Institute of the German Federal Railways showed that the respective sandwich samples have a flammability rating of B3 - "slow burning". This is the second from top grade on the DIN 4102 scale.

Production of the cab

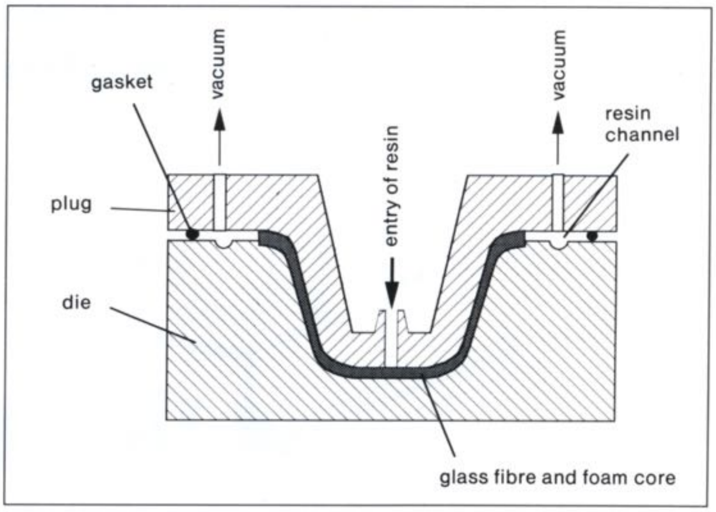
As the cab is relatively large, it is constructed from four individual components, the front, the roof and the two side panels. This makes it easier to manufacture and aids the production process as well as storage before assembly.The individual components are bonded together by means of a structural adhesive.

Manufacturing Process

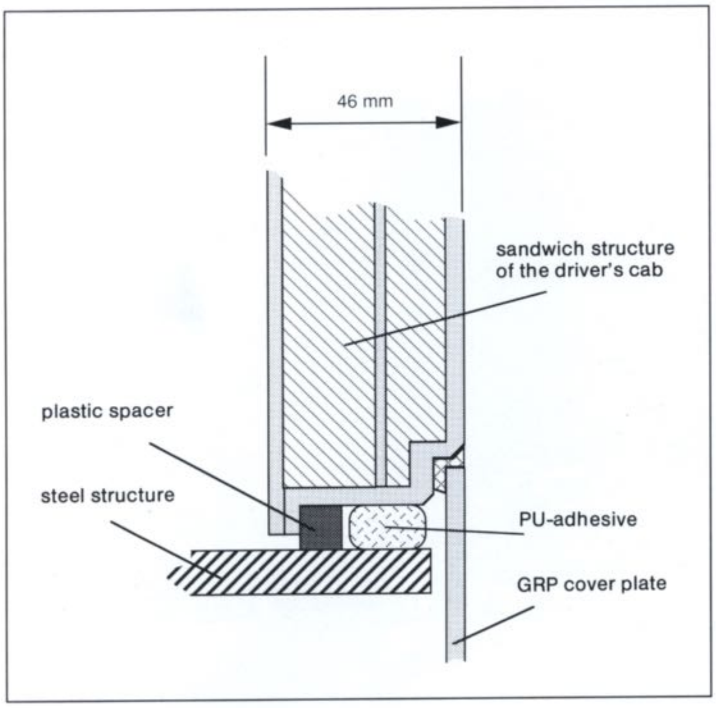
Bearing in mind the size of the production series envisaged (between 50 and possibly several hundred), either the hand lay-up method or the vacuum injection process was suitable. However the vacuum injection process, which was ultimately selected, offers the following advantages when compared with the hand lay-up method:

- Only minor dimensional variations between one piece and another, since warpage due to shrinkage during the hardening process can largely be avoided,
- smooth surfaces on both sides,
- constant high quality throughout the whole series,
- better strength combined with lower weight because of the higher fibre content,
- quick economical and reasonably priced production whereas the hand lay-up method requires a slow build up of individual layers to avoid warpage,
- efficacious protection of workers as the casting process causes virtually no emissions.

However making of the necessary moulds for the vacuum injection process requires a great deal of effort and know-how. A number of intermediate moulds have to be made, — e.g. the master pattern, the intermediate female tool, the master male tool etc. — before the inner and outer moulds for production are obtained. The quality of the final product de-



Schematic portrayal of the method and course of production in the vacuum injection process (Drawing Saurer).



Schematic diagram showing the way the driver's cab is bonded to the steel body (Drawing SLM).

pends decisively on the quality of the production moulds.

The dry glass fabrics, already cut to size, the foam cores and the inserts are placed into the female tool. Then the male tool is put into place and the resin sucked into the space between the tools by means of a vacuum.

Attaching the driver's cab to the body

High demands are made of the joint between the plastic cab and the steel body. It must be able to withstand all possible stresses during use and to cope with production tolerances of 1 to 5 mm. The driver's cab is subjected to large pressures when two trains pass each other and when they are travelling through tunnels. Therefore the joint must guarantee absolute tightness. The high stresses which result from the differences in thermal expansion of steel and plastic must also be absorbed. Of course the same durability is demanded of the joint as of the cab and the body. And it also has to be resistant to climatic influences and the effects of mechanical washing units.

Different possible types of joint were investigated:

- Bolting and sealing,
- conventional adhesive,
- elastic adhesive and additional bolting
- elastic adhesive without additional bolting

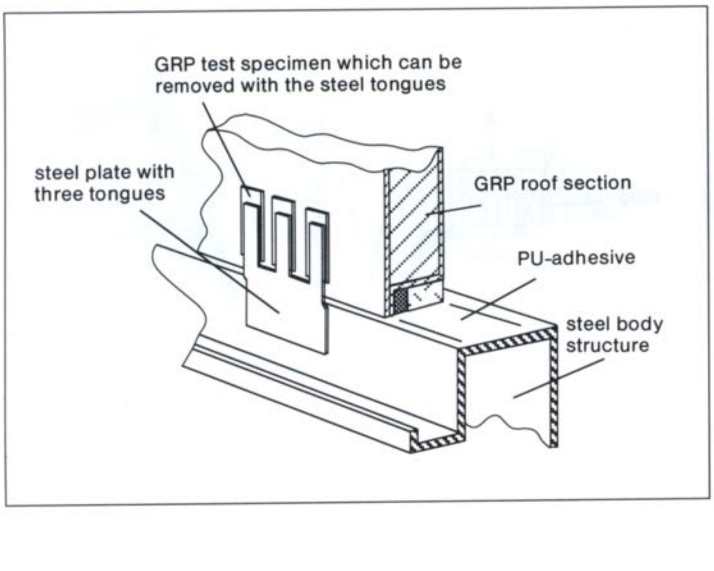
The size of the components to be joined proved to be a special difficulty. This together with the differences in the coefficients of expansion (12 x 10 to the power of -6/K for steel and 30 x 10 to the power of -6/K for GRP (assuming a change in temperature from -20 to + 80 degrees centigrade) cause differences in length of up to 5 mm. If this expansion is not allowed to take place huge forces will be created at the joint with corresponding stresses on the whole structure. Huge forces are also to be expected in the case of re-railing if the joint is too rigid. A finite element analysis of the driver's cab however showed that even these stresses could be absorbed theoretically.

So technically the most convincing solution to the problem was to bond the cab to the body with an elastic adhesive.

Extensive tests were carried out with various adhesives from different manufacturers in order to discover the best way to guarantee the security of the joint. The properties of different adhesives were checked, especially their adhesion to various surfaces pretreated in different ways, and with different adhesion promoters under varying stresses (tensile stress and shear stress).

In the end it was decided to join the cab to the body by means of a highly elastic rubber-like polyurethane adhesive. This adhesive achieves shear strengths of about 5 N per square mm and an elongation at break of about 500 %, whereby exclusively cohesive fracture behaviour was observed.

To provide a way of checking the bonded joint in the long term, three bonded test specimens are fixed on each cab of the locomotive. These test specimens are made at the same time as the real joint between the cab and the body. They "travel" with the locomotive in an exposed position and, like the real joint, they suffer similar deformations, changes of weather, and the effects of washing. The first test specimen is checked immediately after bonding, in order to reveal any defects in the bonding. The other five test specimens are removed at intervals from one to ten years and tested in the laboratory. In this way reliable information is available at all times about the state of the adhesive bonded joint.



Perspective drawing showing the way the plastic cabin is bonded to the steel structure and the three bonded test specimens (Drawing SLM).

Future prospects for the use of Plastics in Locomotive Construction

There are three reasons why plastics should be used more and more in the construction of locomotives:

- High speed locomotives will need to be built with even less weight then now.
- The trend towards rounded aerodynamic shapes is beginning to be seen – some years after it was seen in the automobile industry. These shapes are easier to reproduce in plastic.
- Plastic is normally more cost effective, particularly in relation to overall costs. For example, the plastic cab of the Locomotive 2000 has no need for additional thermal or sound insulation, nor for inner jackets, anti drumming treatment or inside coatings.

In the longer term it is possible to imagine that other parts of a locomotive will be made of plastic rather than steel, for example:

- The bogie frame, where there is a particular need to reduce weight in order to improve dynamic properties at high speed. In Germany experiments are already taking place with fibre reinforced plastic bogies.
- Compressed air containers – in the Locomotive 2000 filament wound pressurised containers are being used for the first time. A container with a volume of 480 litres and an operating pressure of 10 bars weighs 52 kg, whereas a comparable steel container weighs 129 kg. GRP containers also react better to fire and do not explode. As yet however plastic containers cost more than steel ones.
- Unsprung wheel discs and axles, where reduced weight is also desirable.

A valid reason for using fibre reinforced plastic on a large scale is certainly its better overall cost effectiveness. This has already been achieved in several applications.

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The bogie rides, the body glides

SLM's shifting axle drive bogie features radially self-steering wheelsets within the entire range of tractive and braking power. That effectively minimizes wheel-rail forces.

When the bogie negotiates a curve, regardless of tractive effort, the angle of attack of the outer wheel on the leading axle is drastically reduced, avoiding friction and minimizing wear on both wheel and rail. If you want an economical, peaceful glide, consider bogies by SLM:

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Locomotion at its best

The ultimate combination

Combining extremes is a speciality of the Swiss. In a country where valley lowlands alternate with mountain peaks, bogies, for instance, encounter an extremely challenging countryside.

Based upon the contrasting requirements of hillside travel, SLM has engineered a bogie capable of 230 km/h on the straight and 104 km/h in a curve of 300 m radius. For this combination of extremes, various features of SLM bogie technology join forces, including decoupled masses, elastic and floating suspension for motors and gears, hollow-shaft cardan drives and self-steering radial alignment of wheelsets. If you're looking for the versatility of the ultimate combination, consider bogies by SLM.

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