

IMPROVING THE SERVICE LIFE OF SEALED CLADDING JOINTS THROUGH A TOTAL QUALITY MANAGEMENT APPROACH

A.T. Wolf
Dow Corning S.A., Seneffe, Belgium

Abstract

Sealants and gaskets are among the components of a cladding most likely to fail. Despite their fundamental role in the weatherproofing and thermal insulation of the building envelope, they receive little consideration from initial selection to final use. A large percentage of the cladding seal defects and failures can be attributed to poor workmanship, the lack of proper site supervision and faulty fabrication. The paper suggests that 'sealed joint quality' can be defined as the extent to which the sealed joints conform to established requirements. The paper shows how a more complete set of requirements can be established by use of fault tree analysis. The paper recommends that cladding contractors should implement an appropriate quality management system which is aimed at establishing a commitment to quality, improving the quality output, and providing confidence that acceptable quality has been achieved. Implementation of effective quality management in a cladding project will not only ensure adequate supervision, but also proper workmanship. A system of checklists and routine inspections can be used to ensure that the sealed cladding joints conform to the specified requirements.

1. Introduction

For centuries buildings have been constructed to house inhabitants and to protect them from the external environment. In order to achieve a habitable indoor environment, a necessary function of the building envelope is to screen off the wind and rain. Various systems of weather-proofing building envelopes have been developed over the past 50 years, however, water leakage remains a major problem faced by the building industry. Water can ingress into the building via various pathways; however, the most common entry is via the building envelope joints. Not only are these joints a result of modern prefabricated, modular building techniques, they also provide a vital function in the building envelope by accommodating movements resulting from the inherent or

externally induced changes in the dimensions of the building elements. Nature teaches us that building joints are essential. If we disregard the need for properly designing and installing joints, they will form by themselves. If we disregard the need for properly sealing the joints, water will penetrate into the building. Despite nature's simple lectures, the building industry is still struggling nowadays with the problem of providing weather-tight joints, despite years of research and development of new joint seal systems.

Various systems of weather-proofing building joints have been developed, each with its specific pro's and con's; however, none of the systems has a track record of reliably preventing water and air ingress into a building over a reasonably acceptable period of time. Once the seals have lost their weather-proofing function, a building leaks and the thermal insulation performance of the building envelope gravely deteriorates.

A survey carried out in the United Kingdom in 1990 [1] revealed that 55% of the building joints examined had failed within ten years and that only 15% had lasted for more than twenty years. The findings of this survey mirrored those of a similar study undertaken in Japan in 1984 [2]. The cost of resealing a building is often high; the cost of sealing buildings as part of new build is of the order of 3% of the total cost of the cladding, while the cost of resealing joints following failure may be as high as 15% [3].

Why do building joint seals fail so frequently and prematurely? The author believes that the root problem lies in the fact that the total responsibility for the creation of a building structure is divided between many different people and organisations and, for large projects, extends over a comparatively long period of time. If buildings were industrial products that rolled off a company's assembly line in the same manner as cars, household appliances or most modern consumer goods do, the problem of leaky buildings would have been solved years ago. In this imaginary world, manufacturers of leaky buildings simply would not be able to compete based on today's quality standards.

In the early 1960's, the rubber seals around many passenger car doors leaked. Still in the mid 1970's, the seals of many dish washers leaked badly. If one buys a car or a dish washer today and finds it to leak, this is the exemption to the rule. So what has changed in the manufacture of cars and dishwashers that apparently has not yet affected the building industry? Is it the development of new materials or designs? Certainly not, since plenty of new materials and joint designs have been developed over the past 30 years or so. What is different, in this author's opinion, is how quality management systems, reliability theory and service life testing analysis were implemented in the various industries. With this paper, the author hopes to show how the building industry might be able to learn from the progress made in other industries. Since the author is most familiar with wet applied (gun-grade) sealants used in sealing building claddings, he will use this application as an example during the discussion. However, many of the comments made apply to other building joint weather-proofing systems as well.

2. The cladding system supply chain

The term cladding embraces a broad range of building envelope constructions ranging from traditional systems, modern curtain wall systems, to prestigious structural glazing systems. Cladding is either sold as a standard system or designed and manufactured specifically for a contract. Cladding systems comprise a large number of components, each with a multitude of types, available from numerous manufacturers as proprietary products.

Figure 1 shows the most fragmented cladding systems supply chain, which is typical for the erection of small scale, standard curtain walls; an activity which represents the largest market segment [4]. Two less fragmented supply chain models can be distinguished and can be roughly related to the type of cladding and the size of the contract:

- integration of design and manufacture, i.e. integrated primary cladding sections supplier and cladding contractor (medium-range system manufactured to contract),
- integration of design, manufacture and installation, i.e. fully integrated cladding contractor (high-end system manufactured to contract).

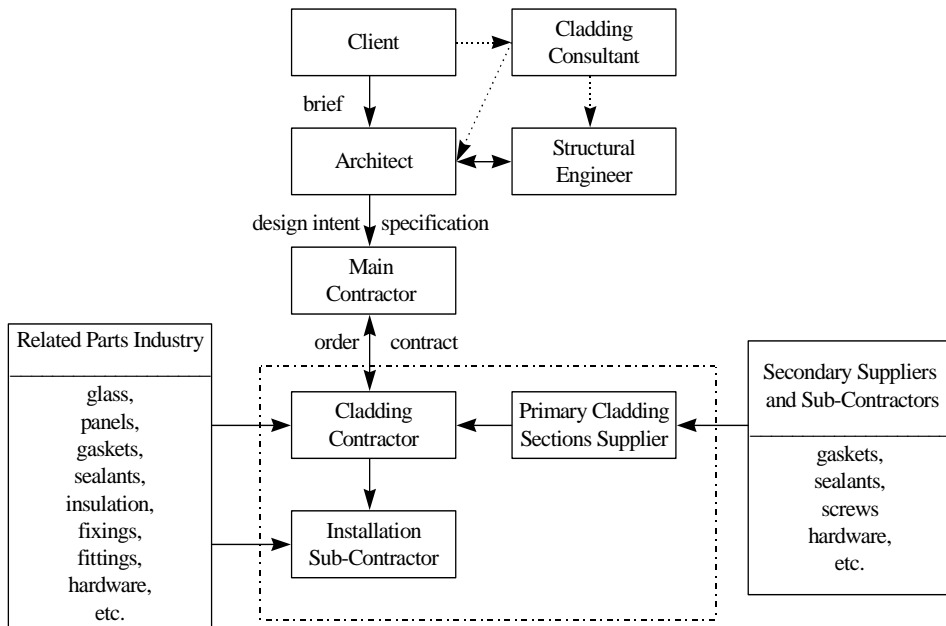


Figure 1: Cladding industry supply chain (adapted and modified from [4]).

In the most fragmented supply chain shown in Figure 1, the cladding system components are supplied to a franchised fabricator for arrangement to suit the building. The fabricator procures components that are non-standard, produces a design that integrates all of the components into the system and machines components prior to assembly on site [4]. The crucial function of the cladding contractor is that of an ‘integrator’, both in terms of the large number of components within a cladding system and in terms of the cladding system as a whole with the building. The cladding contractor can only achieve these functions successfully by effectively co-ordinating his activities with those of the cladding section supplier, the related parts suppliers, the installation sub-contractor and the main contractor.

3. Problem analysis: failures and failure modes of building cladding systems

Failure is said to have occurred when a component or system does not function with design intent; a failure mode is the manner in which a component or system failure occurs.

A study [5] conducted in 1993 within the building industry in the United Kingdom revealed that 35% of curtain wall failures was attributable to poor workmanship. The design, supervision and fabrication of the curtain walls accounted for 22%, 16% and 9% of all failures, respectively. The most common causes of curtain wall failures identified by this study are shown in Figure 2.

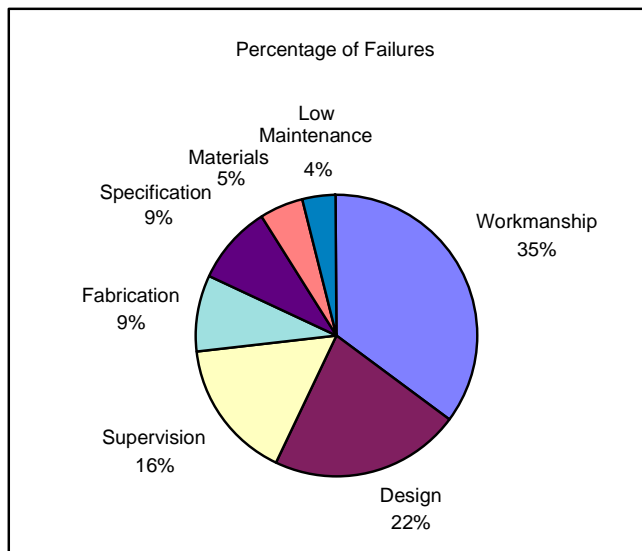


Figure 2: Causes of curtain wall failures.

The same study [5] revealed lack of weather-tightness as the most common failure mode (31% of all failures). According to a qualitative survey of construction and cladding industry professionals conducted in 1997 in the United Kingdom, water penetration remained the most frequent failure mode of cladding [6]. A quantitative study of over one hundred cladding systems showed a first time pass rate for static water penetration of 26% [7]. This finding substantiates water penetration as unequivocally the most common cladding failure mode and indicates a complete lack of fitness for purpose of almost three quarters of the cladding systems tested. Since this study was carried out on brand new cladding systems, it also suggests major short-comings in the design and fabrication of the joint seals.

The 1993 study [5] showed that component failure represents 58% of all curtain wall failures and, not surprisingly, sealants, flashings and gaskets, which represent the first line of defence against water penetration, account for more than half of the component failures. A detailed analysis of the component failures are shown in Figure 3.

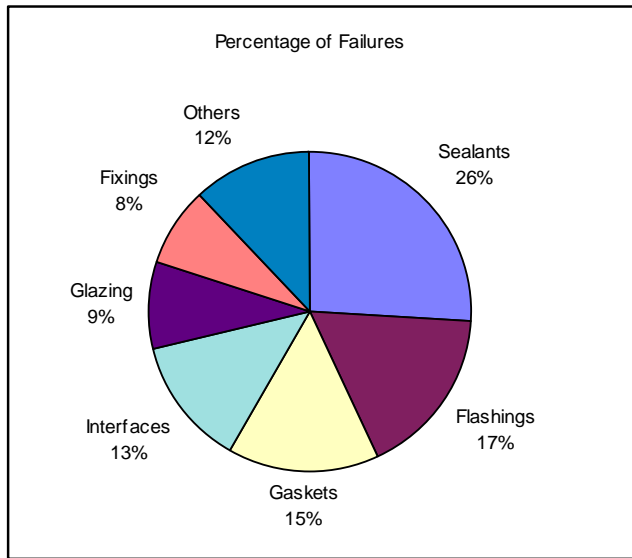


Figure 3: Component failures in curtain walls.

Sealants, gaskets, glass and metal finishes were also identified as the components of a cladding most likely to fail according to a qualitative survey conducted in 1997 in the United Kingdom [8]. Subsequent investigations revealed these component failures are caused by inappropriate selection and use and that the above four components receive too little consideration from initial selection to final use. For example, despite their low cost and fundamental role, sealants can be a low priority, an afterthought or even the target for cost savings on a cladding project [4].

4. Quality and life cycle cost

The previously cited failure analyses clearly suggest that the performance of cladding systems could be substantially improved by focusing on the design, workmanship and supervision involved in the sealing of building envelope joints.

According to Cornick [9], the problem with the word quality is that, in particular situations, it can have different meanings for different people. In many ways, the problem of defining quality is more acute in the construction process than in any other production field. Since the total responsibility for the creation of a building structure is divided between many different people and organisations, it is essential to use a definition for quality that allows it to be communicated, managed and ensured. It is also essential that quality means the same to all parties involved in the construction process.

Two simple definitions for quality can be derived [9]. Quality is either fitness for purpose or, secondly, conformance to requirements. However, the only definition which is suitable for a quality management programme is that of conformance to requirements.

By including all performance needs in the list of requirements, both a level of excellence and a fitness for purpose can be achieved from the basis of conformance to requirements. Requirements can be clearly defined, communicated and conformance to requirements can be reasonably assessed. Thus, 'sealed joint quality' can be defined as the extent to which the sealed joints conforms to established requirements (e.g. building codes and practices, performance and durability standards, et cetera).

As a first step in ensuring quality, requirements need to be established which reflect the performance needs of the specific application. For applications with similar performance needs, the requirements can then be grouped together in building codes and practices, performance and durability standards, and similar technical regulations. As will be shown below, an analysis of failure modes and mechanisms can serve as a tool in establishing a more complete set of performance requirements.

In order to achieve conformance to established requirements, a quality management system needs to be put into place that operates at all levels within an organisation and which is aimed at establishing a commitment to quality, improving the quality output, and providing confidence that acceptable quality has been achieved. Quality management thus covers all the actions which the project management takes to achieve the quality policy. The quality policy embraces the overall quality intentions and directions in achieving the client's requirements, as formally expressed by top management. Quality management, thus, can be defined as all planned and systematic actions necessary to provide adequate confidence that an item or facility will perform satisfactorily in service.

The life cycle cost of a building structure can be defined as the total cost of planning, designing, erecting, acquiring, operating, maintaining, and disposing the building over its service life. Service life is defined by facility managers in financial terms as the period of time, during which it is more cost effective to maintain an asset than it is to fund the annualised replacement [10]. If the management of quality during various phases of the building life cycle is poor, the life cycle cost will be high. Poor quality results in more work-in-process, more repairs, more rework and more inspections and, hence, in higher cost.

5. Defining quality: requirements for long-term performance of sealed joints

Failure of a sealed joint can occur by various failure modes. The following list highlights some examples of failure modes that may occur (note that not all failure modes are related to the weather-proofing function of the sealed joint):

- failure of sealant-to-substrate interface,
- cohesive failure (within sealant),
- spalling (of substrate),
- staining,
- dirt pick-up,
- microbial growth,
- others.

The failure of a sealed joint can generally be attributed to a number of factors (often also referred to as ‘root faults’). Some of the typical root faults involved in sealed joint failures are:

- design factors,
- application factors,
- product factors,
- environmental factors,
- service factors.

So-called fault trees provide a systematic method of analysing the relationship between root faults and a failure mode caused by a specific degradation mechanism. Fault trees have been successfully used in the electronic and aerospace industries for identifying the relationship between basic faults, degradation mechanisms and failure modes [11]. Their use for construction applications is still in its infancy.

Figure 4, shows, as an example, a partial fault tree with some sub-divisions for the failure of the sealant-to-substrate interface (loss of adhesion) due to hydrolysis reactions (the key contributing basic faults are shown in *italics*).

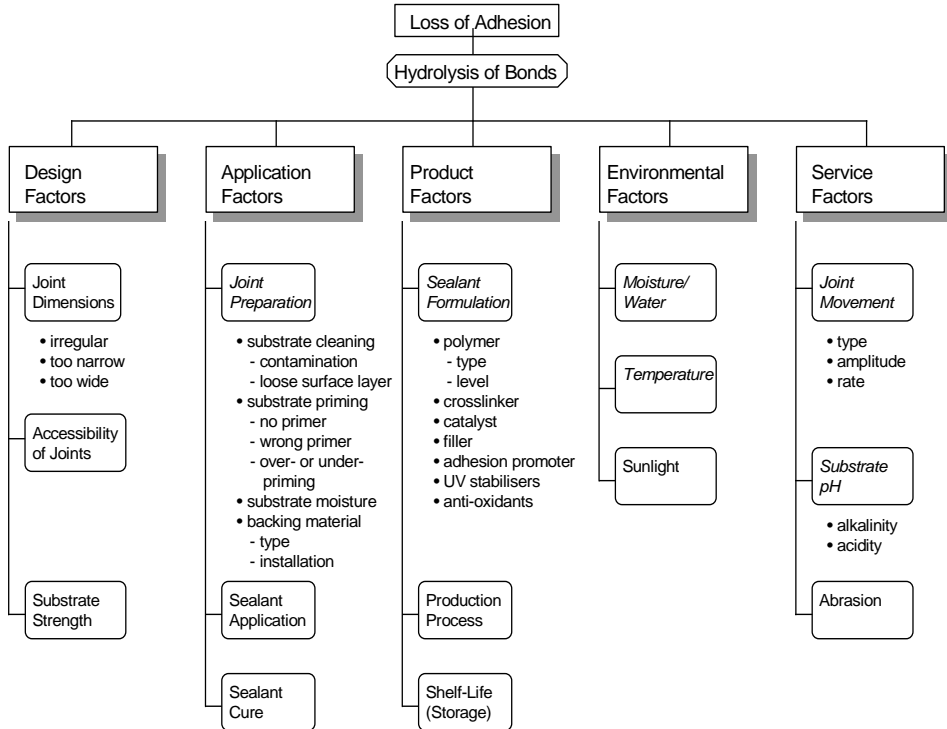


Figure 4: Partial root fault tree for failure of sealant-to-substrate interface.

Root faults are linked to a failure mode by a degradation mechanism. In the above example, loss of adhesion is caused by the hydrolysis of chemical bonds which in turn is affected by the joint preparation, the sealant formulation, the presence of water, elevated temperatures, joint movement and substrate pH. Fault trees, thus, allow to trace specific failure modes back to the basic faults that cause these failures.

It is important to note that the same failure mode, for instance ‘loss of adhesion’ in the above example, may be linked to another degradation mechanism, for instance ‘incomplete substrate wetting’. Adhesion loss caused by incomplete substrate wetting would, however, be linked to a different set of basic faults; in that case, joint preparation, sealant application, sealant formulation, moisture content of the substrate, temperature at time of application, and joint movement.

The purpose of establishing fault trees for the various failure modes is to ensure that all basic faults have been identified. Once all basic faults have been identified and the interactions between the various root faults have been investigated, the basic faults and methods of dealing with them can be described in separate documents, such as in:

- design codes,
- best practices for applications, and
- product performance and durability requirements.

The systematic use of fault tree analysis could substantially improve the process of defining the design, application, performance and durability requirements for sealed joints. As a first step, the use of this tool would help us by identifying gaps in our understanding, guiding further research, and providing an efficient method of documenting the accumulated knowledge. As a second step, the use of this tool would guide us in the composition of the standards drafting committees by highlighting the critical skills and key expertise necessary for the drafting of a specific document, and in the actual development of the standard by providing the scientific underpinning.

Initial research by the RILEM TC139-DBS committee members suggests that the most urgent need in defining quality is in the development of performance driven durability test methods for building sealants that better predict the actual in-service performance of these materials [12]. On a conceptual basis, reliability theory and service life testing analysis could then be used to validate these test methods and to predict the actual performance in service by developing a mathematical connection between laboratory and field exposure results (development of so-called 'service life models'). However, until today, only a few service life models have been developed for polymeric materials and those apply only if the observed degradation meets certain mathematical conditions [13]. It is by no means certain that such a model can be established with reasonable investments in cost and time, due to the complexity of sealant formulations and the resulting multitude of interactions between formulation components which all have an effect on the durability of the sealant. One of the key obstacles to the development of a service life model for sealants is the lack of consistently reported experimental information. Thus, while it may take many more years to develop a scientifically based service life model for sealants, it is essential that we start now to collect, evaluate and report information in such a manner that it can be used as a foundation for such a model.

However, given the lack of a widely accepted durability test method and the increasing pressure on the sealants industry to reduce product development cycles now, it is also essential to develop a standardised, internationally recognised, accelerated durability test method within the next few years. Obviously, such a test method cannot be founded on a scientific service life model, but rather needs to be based on expertise and experience. We will need to accept the fact that such an interim test method most likely will not produce a high correlation between the performance in accelerated artificial ageing and in actual service joints for each and every sealant. We should attempt to select the test parameters in such a manner as to bias the test method towards the better performing sealants. As a result, some sealants that perform well in the field may fail the test method. However, a more important consideration will be that those sealants that pass the test method will perform adequately in the field and will not fail prematurely.

6. Implementation of quality management

Defining the design, application, performance and durability requirements for a specific construction project and selecting the correct materials to the correct specification is a step in the right direction. However, whilst an improvement in many cases, it may not guarantee satisfactory performance of the building cladding seals, if the implementation of these requirements are not ensured by proper supervision and quality assurance procedures during the fabrication and installation processes.

Layzell has highlighted several factors that can derail a quality specification during the production and construction phases [4], namely:

- installation errors,
- fabrication errors,
- subversion of specifications,
- poor supervision,
- poor motivation,
- contractual pressures, and
- poor communication.

Since any of these derailing factors are likely to occur on a construction project, one needs to anticipate them and establish a quality management programme prior to the beginning of a project. The first and most basic step in establishing a Project Quality Management Programme (PQMP) is to formulate written requirements that specify the roles and responsibilities of all project participants. The total PQMP applies to the following sequential project steps:

- Planning
- Budgeting
- Design
- Construction Documents
- Bidding
- Construction

A PQMP representative should be designated (or contracted) by the client, the cladding consultant, the main contractor or the cladding contractor. It is important to analyse, plan and document how the designated PQMP representative will manage and control the quality aspect of all construction activities. Since the cladding industry encompasses a large number of specialist contractors of varying levels of expertise, it is important that this plan is geared to fit the contractor's skills and needs. Since over half of the failures of the building cladding are due to poor workmanship, the lack of proper site supervision and faulty fabrication, it is obvious that more control needs to be exercised over these specific elements of the works.

The PQMP plan therefore should address the following aspects:

Preparatory phase:

The preparatory phase is essential in establishing a Quality Assurance (QA) programme for a cladding project. During this phase, the following objectives should be achieved:

- All personnel involved with the joint sealing operation is aware of the key requirements for achieving the desired sealed joint performance.
- Written QA procedures are established, communicated and implemented - the need for documenting QA results is well established - an action plan for implementing QA procedures has been established that specifies what needs to be done, where it needs to be done, when it must be done, who is to do it and how it must be done.
- A relationship with the sealant manufacturer is established - discussions with the sealant manufacturer will identify the key factors that must be assessed for a specific project.
- The sealant manufacturer's instructions on substrate preparation and sealant installation procedures and all applicable standards and codes of practices are available and have been reviewed with and are made accessible to all key personnel.
- Test reports documenting sealant adhesion, performance or compatibility data specific to the project, substrate or other contact materials are available to all key personnel. The sealant complies with applicable national or international performance standards (e.g. DIN 18,540, ISO 11,600) or quality kite marks (e.g. SNJF)
- Joint design and location are reviewed to ensure they meet all applicable standards or specifications and are accessible.

Fabrication:

Every stage of the fabrication must be inspected for cleanliness, accuracy, and consistency of application and compliance with the design requirements. The following checks should be performed:

- incoming sealants: acceptable condition of the sealant containers, material is within manufacturer's specified shelf-life and the sealant cures properly;
- quality of substrate cleaning: the type of cleaner, type of towel, cleaning procedure, time duration of cleaning and evaporation of cleaner;
- quality of priming (if required): the type of primer, application method, coverage, time duration of priming and drying of primer;
- quality of sealant application: sealant product is the one specified for the project, the quality of mixing and metering accuracy is acceptable in terms of mix ratio and uniformity of mix as well as sealant cure rate (for two-part sealants);
- quality of sealant application method, ensuring complete joint cavity filling and substrate wetting;

- quality of tooling of sealed joint;
- sealed joint dimensions - periodic check at predefined intervals if actual sealed joint dimensions correspond with design.

QA testing during fabrication:

- Test specimens are tested according to agreed-upon or standard test procedures (test specimens are prepared with substrate samples taken from actual production sections).
- Sealed joint dimensions are inspected (by cutting out sections at planned intervals).
- Sealant application quality is inspected, especially the completeness of joint filling, the placing of the back-up material, and substrate wetting. Checks for bubbles and voids are performed.

Mock-up testing:

- Static and dynamic water penetration tests are performed on pre-installed cladding sections (this activity is generally only done for larger projects).

Installation site quality control:

- Climatic conditions on site (temperature, humidity, substrate wetness) are monitored and recorded in a site log.
- The same QA procedures and checks as during the fabrication stage apply.
- Adhesion of the sealant is checked at predefined intervals.

Incorporation of the above activities into a PQMP plan will improve the standard of workmanship by rigorous, knowledgeable inspection and supervision and promote the desire that every process associated with the joint sealings is carried out satisfactorily. The implementation of a PQMP plan is generally most effective by working with

- experienced and certified installers, supervisors and outside inspectors who have a known level of experience and expertise; and
- reputable sealant manufacturers who produce sealants with a 'pedigree' and who provide technical consultation and up-to-date documentation already during the project planning phase.

From a PQMP manager's perspective, companies who already have a reliable quality assurance system in place are easier to interact with, since they recognise the need for having their products and services comply with certain specifications. While not a necessity for ensuring proper quality programmes, ISO 9000 certification documents that certain internationally agreed requirements are met by a company's quality management system.

The application of total quality management principles during the planning, design, construction and installation phases results in less failures of cladding seals. A recent study, published in France [14], revealed a significantly lower failure rate with structural glazing facades than with conventional cladding. Obviously, some of the difference in failure rates may be attributed to the design differences between the two systems. The key contributor to the better built quality of structural glazing facades, however, is the consistent application of a total quality management approach (a must for this cladding technique) which ensures that the right materials are being specified and used correctly.

7. Conclusions and recommendations

The following conclusions can be drawn:

- There is problem with the poor quality (low service life) of cladding seals.
- A large percentage of cladding seal defects and failures can be attributed to poor workmanship, the lack of proper site supervision and faulty fabrication.
- Sealants and gaskets are among the components of a cladding most likely to fail and receive too little consideration from initial selection to final use.
- Quality cladding seals can only be produced if a set of specified requirements is developed and if the design, workmanship and products involved conform to these requirements.
- Assurance of the required conformance can only be achieved by means of an effective quality management.
- Implementation of effective quality management in a cladding project will not only ensure adequate supervision, but also proper workmanship. A system of checklists and routine inspections can be used to ensure that the sealed cladding joints conform to the specified requirements.

The following recommendations are made:

- Fault tree analysis should be used in the identification of basic faults, their interactions and their relationship to specific failure modes and degradation mechanisms. This method will allow to develop a more complete documentation of basic faults and methods of dealing with these basic faults (such as in design codes, best application practices, product performance and durability requirements).
- Performance driven durability test methods for building sealants should be developed that better predict the actual in-service performance of these materials. These methods should be validated using reliability theory and service life testing analysis.
- Cladding contractors should implement an appropriate quality management system which is aimed at establishing a commitment to quality, improving the quality output, and providing confidence that acceptable quality has been achieved.

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