

MODULAR DESIGN AND ASSEMBLY OF AUTOMOTIVE AND ARCHITECTURAL STRUCTURES: PRODUCT INTEGRATION THROUGH ADHESIVE BONDING

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Summary

This paper analyses advances in design and manufacturing methodology based on system modularisation in the automotive and building & construction industries and offers novel, fully validated technology for modules assembly by adhesive bonding. It is shown, how application of appropriate modularisation methodology through sub-division of the entire system into principal system platform and independent functional or stylistic modules enables identification of components common to an entire family of product, and those which facilitate product re-configuration and stylings. The latter category of sub-components are easily integrated into the final structure by mounting onto the principal system platform through interfaces facilitating rapid assembly and/or disassembly of the product. Through adoption of modularisation, the pivotal structure elements such as automotive framing systems or high-rise building's curtain wall framing and cladding can be quickly and cost effectively designed, re-designed when needed (for instance for re-styling or refurbishing) and cost-effectively reconfigured through assembly of a variety of designated sub-systems onto the principal system platform. Another aspect of this paper discusses and validates a feasible technology facilitating for surface modification of typical engineering substrate materials (plastics, composites, metals and ceramics) for rapid assembly of structures through adhesive bonding of decorative and/or functional cladding and vision panels to curtain wall structures of high-rise commercial or residential buildings. An identical approach to applications in rapid assembly of automotive modular systems will be presented in the forthcoming paper.

Keywords: system modularisation, automotive, building industry, adhesive bonding

Projektowanie i montaż systemów modułowych w przemyśle samochodowym i budownictwie: połączenie elementów wyrobów metodą klejenia

Streszczenie

W pracy zawarto analizę postępu w metodach projektowania i produkcji opartych na zasadzie systemów modułowych w motoryzacji oraz budownictwie, również technologię montażu za pomocą połączeń klejonych. Przedstawiono, w jaki sposób przyjęcie odpowiednich modułów poprzez podział całego systemu wpływa na podstawową platformę montażową oraz autonomiczne moduły funkcjonalne i stylistyczne. Umożliwiona jest wówczas identyfikacja elementów wspólnych dla całej rodziny produktów, także pozwalających na przekształcenie lub stylizację wyrobu. Moduły autonomiczne są

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łatwo integrowalne w produkty finalne poprzez montaż na podstawowej platformie montażowej przez zastosowanie połączeń standardowych – umożliwiają szybki montaż i/lub demontaż. Wykorzystanie modułowych, kluczowych elementów konstrukcji, jak rama zawieszenia samochodu lub ściana osłonowa wysokościowca i płyty ościenne pozwala na przekształcanie, szybkie i tanie projektowanie, również przeprojektowywanie (np. dla nowej stylizacji lub odnowienia budynku), oraz przekształcanie poprzez montaż różnych nowo projektowanych podsystemów na głównej platformie montażowej systemu. Odrębny fragment pracy omawia łatwą do wprowadzenia technologię modyfikacji powierzchni typowych materiałów inżynierskich (polimery, kompozyty, metale i ceramika) dla szybkiego montażu konstrukcji poprzez klejenie ozdobnych lub funkcjonalnych paneli ościennych lub szkła do ram ścian osłonowych wysokich budynków mieszkalnych i komercyjnych. Identyczne podejście w zastosowaniu do szybkiego montażu samochodowych systemów modułowych będzie przedstawione w kolejnym artykule.

Słowa kluczowe: systemy modułowe, motoryzacja, budownictwo, połączenia klejone

1. Introduction

Modularity-in-design and modularity-in-production, although known and used for more than a century in engineering and manufacturing by various industries such as automotive, machine tools, home and industrial appliances, building and construction, personal computers and other, is being recently re-defined due to increasing demands of customers requiring manufacture and rapid delivery of specifically customised or personalised products satisfying their individual tastes and service requirements [1].

'*On-demand*' product customisation through modification of functionality or rapid re-shaping depending on the functional, aesthetic or fashion-driven requirements either, pre-determined or changed due to suddenly eventuated variation in service requirements are increasingly demanded by the owners and operators of automotive, architectural, military, industrial and other categories of engineered products and facilities. Such requirements can be feasibly satisfied by modular design which is rapidly becoming a new paradigm in engineering design and manufacturing domains [2].

Modular design targets construction of industrial products or systems based on their logical sub-division into smaller functional and/or decorative sub-systems or building blocks which, upon assembly, function as integrated sets [3]. To ascertain the end-product designated performance the individual modules need to be connected by appropriate mechanical, electronic/electrical or other types of interfaces, whose choice strongly depends on the functional and stylistic complexity of the system [1]. Compatibility of modules is ascertained by "design rules" governing: (1) the pre-determined product architecture and designated interfaces, and (2) standardised tests of the system which must demonstrate the following [4]: (a) designated performance of each module, and (b) appropriate interaction of modules assembled into a system. Where needed, interfaces facilitate communication between inter-connected product sub-systems.

Appropriately designed modular architecture of the product sub-divides it into individual modules which can be readily re-arranged into different configurations, i.e. product variants, subsequently creating new design options. Individual modules in their original form or re-styled, can be '*on-demand*'

assembled or dismantled and replaced, thus facilitating rapid assembly and construction of a '*morphing*' real or virtual product.

The analysis and definition of desired functionality of the product generates the product's functional structure. It presents itself in the form of hierarchical composition (assembly) of individual modules connected together through appropriate interface(s) to effectively determine the desired product's configuration.

As emphasised by Baldwin and Clark [4], individual components (modules) can be independently manufactured in various industrial manufacturing facilities as standardised, high quality, completely finished items which are transported to an assembly plant or construction site to be rapidly assembled into a designated structure.

Due to modular structures' adaptability, specific products such as cars, aircraft, ships, buildings, weapons or infrastructure composition can be relatively easily expanded, reduced or otherwise changed by adding or removing individual moduli without altering the principal platform structure of a vehicle or building. Such process facilitates easy change in appearance and functionality, depending on varying demands of the product service performance, architectural style or fashion, and appeal requirements [4]. In this way designated product families can be formed using the initial, or re-styled, or newly developed modules without increasing the product complexity and costs of manufacture.

It is clear from the above that modularity facilitates easy generation of alternative product lines, from the principal platform design allowing assembly of alternative modules that exhibit either the originally designated or new functional and stylistic features, to the end-product in response to changing needs and desires of customers. By properly defining and designing the system interfaces, designers and engineers can flexibly design and manufacture alternative (morphing) forms, functions and functionalities which can be embedded in independent modules. This, in turn, allows on-going development and manufacture of novel forms and their engineered solutions leading to updated or new product lines without the need for replacing the entire structure of the product, which subsequently inherently lowers associated costs at potentially many stages of the process.

This flexibility of design and manufacturing processes is supported by a variety of advanced tools and technologies such as CAD/CAM, High Speed Machining, Rapid Prototyping and 3-D Printing.

2. Automotive Industry: alternative vehicle variants through modularity in design

Automotive OEMs (Original Equipment Manufacturers) vigorously pursue the concept of modular design and platform sharing to minimise their development and production costs due to the platform development costs accounting to approximately 50% of overall costs of a new model launch. In this

quest, definition of the vehicle modular architecture from the viewpoint of ascertaining the critical elements determining its performance, safety and aesthetic/stylistic attributes is of paramount importance.

The under-body, schematically illustrated in Fig. 1, is the key structural component that establishes the structural integrity and stiffness of the vehicle. It provides the platform for integration and connecting all vital car components such as engine, transmission and suspension [5]. Any change to the shape of this under-body will affect all surrounding, interconnected components. Consequently, the integral under-body (Fig. 1a) with its inherently inflexible architecture, limits the development of alternative designs, typically limiting production to a single vehicle variant manufactured at a dedicated assembly line. Any attempt to offer an alternative design variant requires a costly and inefficient redesign process requiring changes/additions to the existing inflexible manufacturing and assembly process.

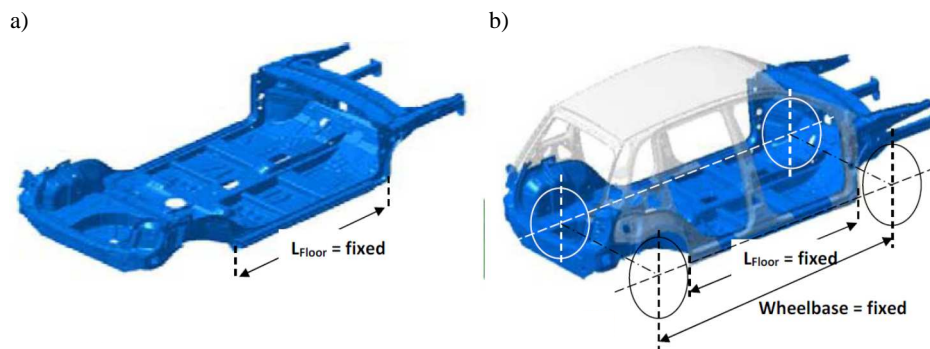


Fig. 1. Integral design of under-body assembly (a), Body-in-White (BiW) with integral under-body (b) (partially adopted from [5])

Due to the above limitations, the integral under-body approach is being increasingly replaced by a modular under-body structure depicted in Fig. 2. Examples of modular design and manufacturing approaches currently used in the automotive industry are illustrated by diagrams presented in Fig. 2 and 3.

Modular design of shared under-body platforms typically comprises the following principal modules:

1. The main floor (MF),
2. Front-end module (FEM),
3. Rear-end module (REM), and
4. Engine compartment (EC).

Diagrams in Fig. 2 explain the principles of modular approach facilitating flexible development of alternative vehicle variants based on selection of appropriate modules. The control of length and spatial configuration of individual modules enables fast and cost-effective customisation of vehicles in response to

the market needs, including in some cases (usually pertaining to higher-end vehicle brands) individual client needs and requests.

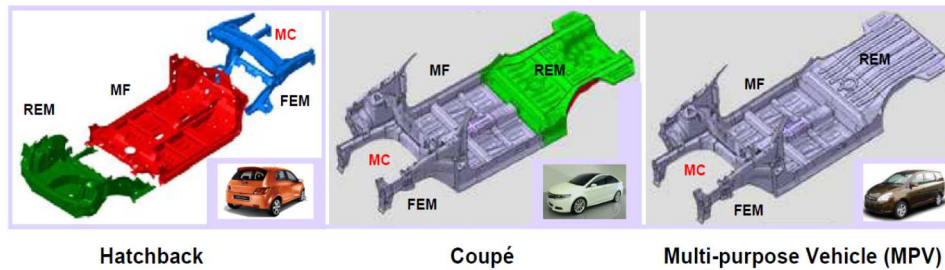


Fig. 2. Schematic illustration of car modular design regarding shared under-body platform common to a range of vehicle variants (Hatchback, Coupé, MPV) comprising flexible modules such as: (i) front-end module (FEM), (ii) motor compartment (MC), (iii) main floor (MF), (iv) rear end module (REM). Practical examples of modular under-body platform in cars manufactured by Proton: Hatchback (Savvy), Coupé (Persona) and MPV (Exora). Note: under-body outlines adopted from [5] and [7]

Further consideration (pertaining to modular design) of all aspects of spatial architecture of the vehicle body, and introduction of optimised interfaces and self-centering connectors, drastically increases manufacturers' flexibility in rapid customisation of the body, including its styling aspects. The scope of flexibility regarding vertical modularity and styling of the body are schematically illustrated in Fig. 3.

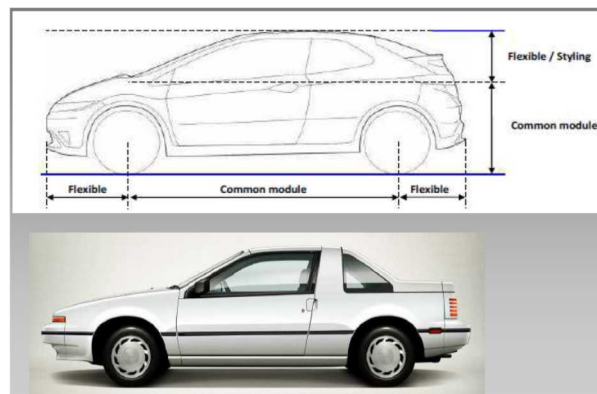


Fig. 3. Schematics of typical modularization approach in car body design by the use of common and flexible modules facilitating rapid customisation and styling of the vehicle's body

It can be seen from Figures 2 and 3 that the introduction of a variable main floor module facilitates the control of vehicle wheelbase, hence facilitating the

manufacture of diversified variants of vehicles such as: hatchback, coupé or multi-purpose vehicle. Additional incorporation of alternative stylised and functional modules of the body enables significant broadening of the style variety and type of functionality of assembled vehicles. The latter is demonstrated by a set of photos in Fig. 4 presenting modular body styling solutions achieved by Nissan in its EXA 1990 vehicles range.



Fig. 4. Flexible control of spatial body architecture and functionality through modular styling approach: Nissan EXA 1990 vehicles range

3. Building and construction industry: modularity in the design and manufacture of Building Façades

In the building and construction sector, modular design and construction has become increasingly popular in the construction, assembly and customisation of residential and commercial buildings.

In the domain of residential buildings, it is predominantly utilised in up to eight-storey high complexes, typically hotels, apartment blocks, student residences, defence accommodation and social housing. This mode of construction is carried out at two levels:

1. On-site assembly of prefabricated room-sized volumetric units. In this mode, the prefabricated units that are fully fitted out and finished (including surface painting and texturing) during their in-factory manufacture are installed on-site as load-bearing 'building blocks'.
2. On-site installation of fully finished functional or structural panels such as external cladding, partition walls, flooring panels, ceilings, balconies etc. In this mode, these individual non-structural elements are inserted into, and affixed to the building's structural frame.

Figure 5 schematically illustrates the principles of modular design and construction at the level of complete multi-storey building with integrated individual wall panels, including definition of principal modular grids essential in modular design and construction.

The primary advantages of modular construction over the ‘on-site’ construction mode are: (i) economy of scale in manufacturing of multiple repeated units, (ii) drastically improved quality and accuracy in manufacture, and (iii) speed of on-site installation. Modular buildings and their integral sub-components can be potentially dismantled and reused, effectively maintaining their asset value.

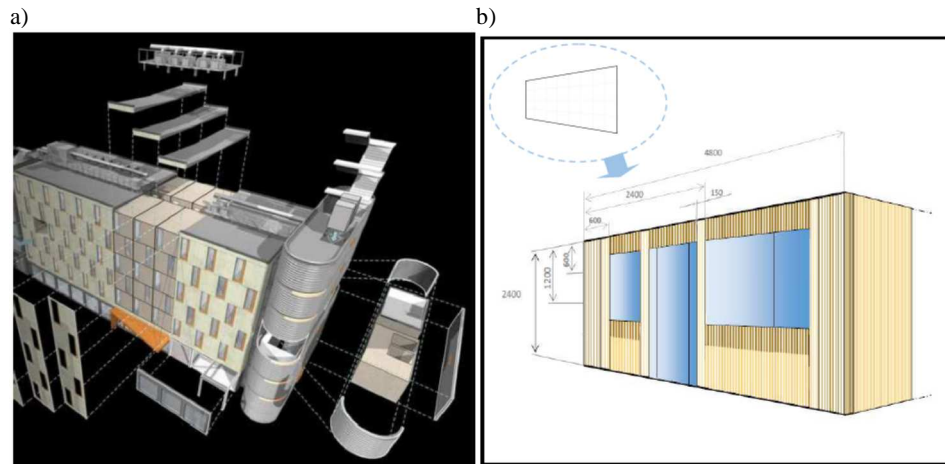


Fig. 5. Schematic illustration of modular design and construction principles at the level of: a) complete multi-storey building, b) individual wall panels (including modular grid definition).

Note: (a) –adopted from [8]

One of the largest areas of modular design and assembly in the building and construction sector are façades. The most commonly used façade systems utilise curtain walls schematically illustrated in Fig. 6, which are widely used as exterior cladding systems in medium and high-rise buildings. They comprise of light-weight, typically aluminium-based framing structures enveloping the entire building. The underlying principal modular grid is based on a lattice configuration comprising mutually interconnected vertical mullions and horizontal transoms. The curtain wall grid is filled in by modular cladding panels utilising glass, metals, composites and thin stone veneers as the main categories of currently used surface finishing architectural materials.

The curtain wall framing is mechanically attached to the main building structure and hence, does not transfer the floor loads which are carried by the principal building structure. The only loads carried by curtain wall are those imposed through external wind pressure and cladding weight; these are transferred to the building structure typically at the individual floor levels.

Architectural façade systems utilise a variety of cladding materials such as aluminium, glass, coated (anodised or powder-coated) metal panels, and composites including green materials such as Wood-Plastic Composites (WPC) which utilise plastic matrix and cellulose fibres as reinforcing materials.



Fig. 6. Construction of curtain walls, architectural systems broadly utilising the principles of modular design; manufacture and on-site assembly: a) Shanghai Tower Curtain Wall (China), b) Science Research Centre, Wausau (Pennsylvania/US), c) Stick System curtain wall Reliance™ manufactured by Oldcastle

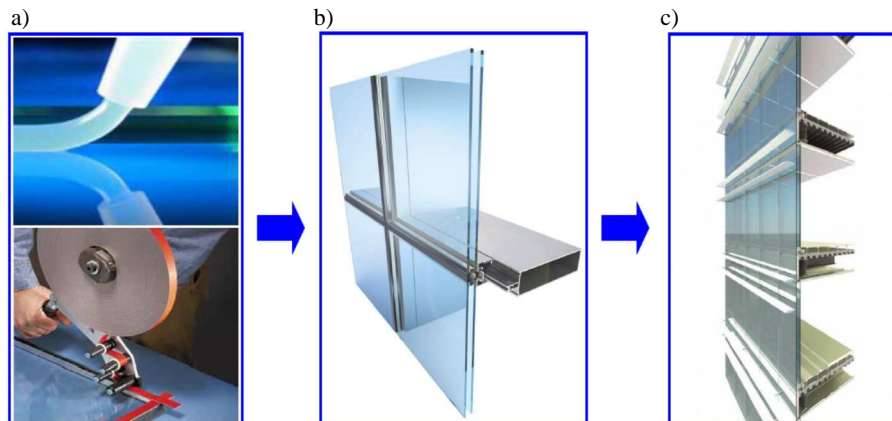


Fig. 7. Schematic illustration of operations involved in modular curtain wall manufacture and installation through structural glazing system utilising adhesive bonding of vision (glass) and decorative cladding panels to framing system attached to building structural frame via mechanical fixing to the floor panels: a) application of silicone adhesive or high-strength self-adhesive tape to the cladding panel; b) details of attachment of façade modular cladding panels to curtain wall framing by elastomeric adhesive; c) bonded cladding panels assembled in curtain wall system through aluminium framing mechanically fixed with building flooring panels

Cladding panels are attached to the curtain wall framing by either of the following means:

1. Mechanical fixing systems, or
2. Adhesive bonding utilising structural elastomeric adhesives (high-rise building curtain walls), or high-strength self-adhesive tapes (low-level residential or commercial buildings).

The experimental part of this paper presents the outcome of our research targeting maximisation of adhesion of silicone structural adhesives (sealants) to nominated categories of typical framing and cladding materials used in curtain wall manufacture, e.g.: anodised aluminium, powder-coated panels, glass, solid wood and wood-based composites.

Figure 7 provides the details of curtain wall manufacture and construction, including the manner of attaching glazing or cladding panels to the light-weight curtain wall framing system and individual floor structures.

4. Adhesive bonding of cladding panels in modular façades of high-rise building

4.1. Engineering substrate surfaces through grafted connector molecules

High strength and durable adhesion of elastomeric structural sealants and adhesives to building façade materials (curtain wall frame and cladding panels) are of paramount importance in the building, construction, automotive and aerospace industries.

It is demonstrated below that significant enhancement of adhesion of such silicone materials can be achieved through the use of surface grafted connector molecules. A simple, industry-feasible technology [20, 21] for surface grafting various types of connector molecules for enhancing adhesion is discussed below. It is shown that surface grafting of silane molecules results in formation of strong molecular bridges between substrates used in façade engineering and structural silicone adhesives leading to significantly improved strength of the bond and its durability. The effectiveness of the interface reinforcement is shown to depend on the following: surface density of grafted molecules; length of individual molecules, and optimum surface density in relation to the length of connector molecules.

4.2. Theoretical considerations

4.2.1. Modes of molecular connectivity between bonded substrate and adhesive

The bond strength and structural performance of adhesively bonded assemblies comprising architectural cladding panels, glass panes and framing materials is controlled by physico-chemical structure, properties and spatial architecture of interphase, an intermediate zone between the substrate and

adhesive schematically illustrated in Fig. 8. It comprises an array of “connector chains” which, at one end, are chemically attached (grafted) to the molecular backbone of a polymeric substrate whilst the unbonded “free end” (see Fig. 8a), on application of chemically crosslinking adhesive becomes chemically bonded to it (see Fig. 8b), or alternatively on contact with a molten thermoplastic or soft elastomeric polymer interpenetrates into the bulk of this material (Fig. 8c) providing adhesion enhancement.

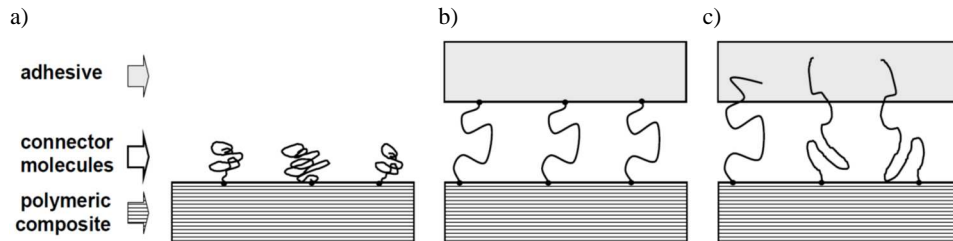


Fig. 8. Schematics of molecular brush interphase between polymeric substrate and adhesive, and that of the connectivity mode: a) prior to bonding: substrate surface decorated with chemically grafted flexible molecular chains (connector molecules), b) connector molecules unfolded and chemically bonded with adjacent adhesive, c) connector molecules interpenetrated into adhesive layer [9]

The mechanisms of alternative interfacial interactions between the surface of polymeric solids onto which flexible molecular chains have been end-grafted, and another polymeric material such as adhesive, through either chemical bonding or molecular chain interpenetration have been explored by numerous researchers [9-24] who determined that the following mechanisms, schematically illustrated in Fig. 9, may contribute to the fracture of such interface reinforced by “flexible connector chains”: (i) chain scission, (ii) chain pull-out, and (iii) craze formation (in ductile polymers).

Increasing the load-bearing capability of the interface (Fig. 8 and 9) relies on inserting, to a desirable optimum, molecular bridges connecting a substrate with adhesive, paint or other material, and the mode of molecular bridge connectivity between these materials. If the both ends of connector molecules are chemically bonded; one end to the substrate and the other to an adhesive (Fig. 9a) whilst surface density, σ , of molecular chains bridging the interface is below the minimum required for exerting stress level causing yielding of one of adhering polymers (Fig. 9b), then on exceeding the failure stress, individual C-C bonds are broken (*at forces of approx. 1 mN*) along the backbone of individual connector chains.

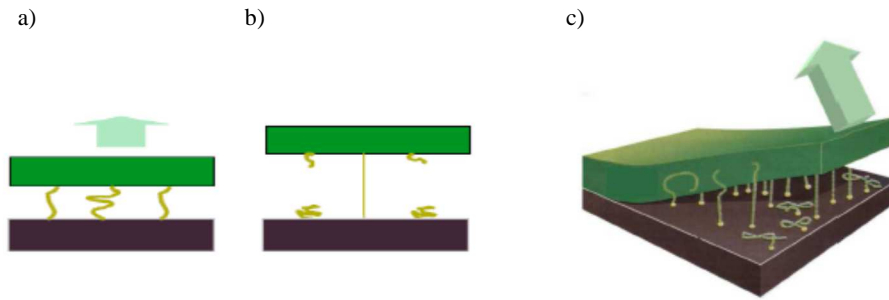


Fig. 9. Interfacial failure mode for two principal connectivity modes of surface grafted flexible molecular chains: (a) substrate-adhesive assembly chemically bonded by an array of molecular bridges before strain application, (b) chain scission along the interface upon excessive deformation causing rupture of single C-C bonds, and (c) surface grafted connector molecules interpenetrated into adhesive layer are gradually extracted from elastomeric adhesive along propagating crack front [9]

Under conditions as above, interfacial fracture occurs along an interface subsequent to molecular chains scission at the stress, S_i , which is:

$$S_i \sim f_b \sigma \quad (1)$$

where: f_b – the force required to break individual chain, σ – surface density of grafted chains.

4.2.2. Surface grafted connector chains chemically bonded with adhesive

Theoretical aspects of adhesion enhancement of solid surfaces by grafted connector chains chemically bonded with polymers (see Fig. 9a and 9b) were explored by Brochard-Wyart and de Gennes [14-19] whose overall work in this area provided foundations of this field of science.

Adhesion forces between chemically inert, smooth solid surface and most adhesives are typically attributed to weak van der Waals interactions. Under external load such systems typically fail through interfacial fracture occurring as a delamination along a sharp substrate-adhesive interface.

Conversely, end-grafted molecular chains at surface density σ (sufficiently low so that each chain acts independently) increase the load-bearing capacity of the interface linearly with increasing graft surface density, as per Eqn. (1) whilst bond energy, G_b , of such “chain-bonded” interface becomes:

$$G_b = W_a + W_b N \sigma, \quad (2)$$

where: W_a – a reversible energy of adhesion between the bare (ungrafted) substrate and the adjacent polymer (van der Waals forces only), σ – the chains surface density, N – the degree of polymerisation of connector molecules, W_b – describes

the energy required to disrupt a dense array of chemical bonds as given by the following:

$$W_b = \frac{U_b}{a^2}, \quad (3)$$

where U_b is the energy of a bond occupying an area of a^2 .

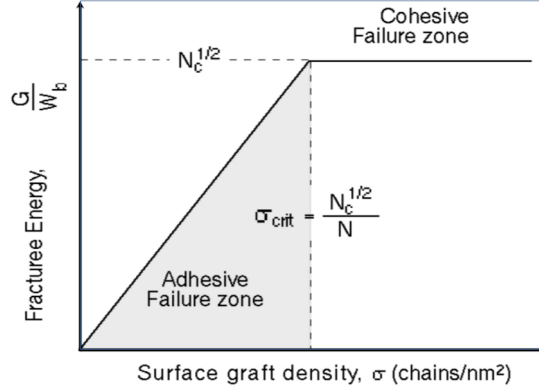


Fig. 10. Fracture energy and mode of interface fracture versus surface graft density, σ , in the case of grafted and chemically bonded macromolecular connector chains [9]

The key findings of Brochard-Wyart and de Gennes [19] are depicted in Fig. 10. These are: (a) an increase in surface density of surface-grafted molecular chains, which are chemically bonded with an adhesive, results in a linear increase of the failure stress and interfacial fracture energy G_i , as per expression (1), (b) the linear increase of interfacial fracture energy (rupture of connector chains only) with increase in graft density occurs up to a certain cut-off value (σ_{CRIT}) provided by expression (4):

$$\sigma_{CRIT} = \frac{N_c^{1/2}}{N} \quad (4)$$

where: N_c – the number of monomers between crosslinks of adhesive whilst, N – the number of monomers per connector chain (degree of polymerisation of connector chain molecules), (c) for graft densities higher than σ_{CRIT} no further increase in interfacial fracture energy (through chains scission) is expected; cohesive failure of a bonded polymer or adhesive is observed.

5. Experimental

5.1. Materials

A range of the following materials typically used in high-rise building construction when bonding glass directly to curtain wall frames was used in experiments analysed in this paper:

Substrate materials:

Polymeric substrates

- Paint finishes on chromate-treated aluminium:
 - Polyester powder coating: PBg (beige-pigmented), and
 - PVDF coating: D2 (white-pigmented)
- Rigid PVC polymer

Metallic substrates

- Organic dye coloured anodised aluminium: K1
- Stainless steel: SS-304

Structural Silicone Adhesive:

- RTV1/795 (Dow Corning): alcoxy-curing system

Graft Chemicals:

Organo-Functional Silanes

- N-(2 aminoethyl)-3-aminopropyltrimethoxy silane: Z-6020 (Dow Corning)
- 3-Glycidoxy-propyltrimethoxy silane: Z-6040 (Dow Corning)

5.2. Substrate surface treatment methods

Substrate oxidation: In our experiments, the surface oxidation of polymeric substrates was carried out either by the use of flame or corona discharge treatment.

Corona discharge treatment

This was performed with a Tantec EST System, model HV 2010 (maximum power output of 1 kW and an output frequency range of 13-30 kHz).

The system comprises the following main units:

- High frequency generator HV 2010 – 240 V/50-60 Hz
- High voltage transformer HT – 10-28 kV output
- Conveyor: controlled treatment speed – 0.1-70 m/minute

In this work, the distance between the substrate surface and electrode was maintained at a constant 2.5 mm, while the treatment speed and energy output were controlled to achieve energy outputs, E_u , from 76 to 755 mJ/mm².

Flame Treatment Equipment

Flame treatment was carried out with commercially available equipment manufactured by the Aerogen Company (UK): FT Laboratory model equipped with a 200 mm long AT 533 burner providing a maximum energy output of 35.1 kW, i.e. 1.755 kW/cm length (120,000 BTU/hour)

Unless indicated otherwise, all flame treatments were carried out with a stoichiometric air/propane mixture controlled to give 1% oxygen excess in the afterburn mixture. During treatment, one side of the polymeric substrate was exposed to a laminar premixed flame. The treatment distance, between the flame tip and substrate surface, while adjustable from 5-130 mm, was kept constant at 10 mm for the current work. Similarly the treatment speed, although adjustable within the range 20-84 m/min., was kept constant at 60 m/min.

Silane preparation and application

Silanes were first hydrolysed with distilled water at a 1:3 silane/water mole ratio for 24 h. The hydrolysed silanes were then diluted with isopropanol to obtain a 0.05 to 1% range of solutions.

The substrates, treated by flame or corona discharge, were immersed in the silane solution for 30 s, after which the samples were dried in air for 30 min, followed by oven drying at 40°C for 4 h. After the initial experiments, the oven drying step was abandoned since no significant difference was observed between the air-dried and oven-dried specimens, and the silane dip was replaced by an on-line spray application. This was carried out immediately after corona discharge or flame treatment, followed by a flash-off with an infra-red drying element placed above the conveyor.

5.3. Test methods

Shear Strength

The shear strength of the adhesive bonds was determined using single lap-shear specimens, 25 mm wide, with an overlap of 10 mm. All substrates were cleaned with isopropyl or ethyl alcohol prior to any further treatment. The bonded specimens were tested in an Instron mechanical tester at a rate of 10 mm/min. Five specimens were tested per experimental point.

Tensile strength

Tensile specimens with 50×12.5×12.5 mm sealant beads, as described in Fig. 11, were prepared and allowed to cure for 2 months prior to testing as described in ASTM C1135 [23].

XPS analysis

XPS analyses were performed on a VG Escalab MkII spectrometer equipped with an Al K_{α} source, non-monochromatized, at a power of 150 W. Samples were exposed to irradiation for less than 30 minutes to avoid substantial decomposition

of the polymer surfaces in the analysis beam. Spectra were recorded at the normal emission of the photoelectron relative to the surface plane of the samples (0°). The spectrometer did not provide for charge neutralization. Elements present were identified from survey spectra, and the atomic concentrations were estimated from integrated peak intensities and published sensitivity factors [27]. Components of the C 1s signal were estimated by curve-fitting using Gaussian–Lorentzian line shapes and a nonlinear background substration. The binding energy scale was calibrated using a value of 285.0 eV for the CH₂ component as an internal reference. The random error in the quantitative analysis of elemental compositions is between 5% and 10% in the present cases.

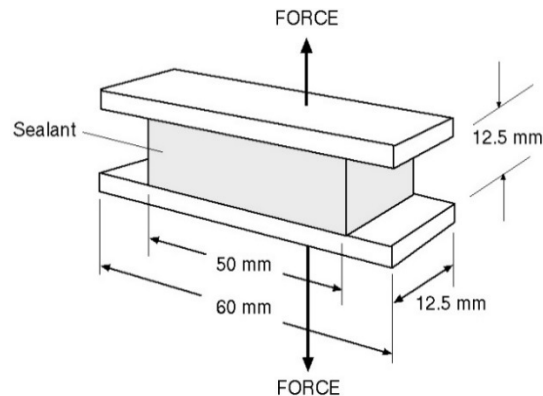


Fig. 11. Tensile specimen configuration

5.4. Interface durability assessment by the combination of mechanical and hydro-thermal stress

It has been shown by Cerra [24] that existing accelerated laboratory procedures for the assessment of the long-term adhesion of elastomeric silicone adhesives fail to consider the fact that the adhesive/substrate interface in a building facade is continuously subjected to a combination of both mechanical and environmental stress. As a result of this, standardised test protocols (eg. ASTM, DIN, BS, JIS and various industry protocols) lack the discrimination necessary to assess relative adhesive behaviour. A novel test procedure has been developed and reported by Cerra [24] which enables improved discrimination of the adhesive strength and overall performance of the elastomeric adhesive/substrate system. The method is based on the simultaneous application of both mechanical and hydrothermal stress, in order to promote adhesive failure at loads below the cohesive strength of the bulk adhesive.

The experiments discussed in this work were conducted by applying dead loads to tensile specimens with $50 \times 12 \times 12$ mm beads of silicone adhesives (see

Fig. 11) while they were immersed in a heated water tank. This was achieved by designing a frame around the tank so that weights, exerting controlled level of tensile stress to the substrate-adhesive interface, could be hung outside it by means of tension lines (Fig. 12).

Table 1 gives the results of tests when the various parameters are changed. In general, the incidence of failure during immersion increases with both, increasing water temperature and stress at the interface.

The results show that immersion in water at elevated temperature, even without stress, has a more severe effect on the cohesive strength of the adhesive than constant stress alone, e.g. compare the tensile strengths for 70°C: 0 MPa (without immersion: 0.56 MPa) and at 20°C: 0.22 MPa (without immersion: 0.91 MPa) with the dry control tensile strength (0.94 MPa). However, the combined effects of water temperature, immersion time and load are necessary to quickly produce adhesive failure.

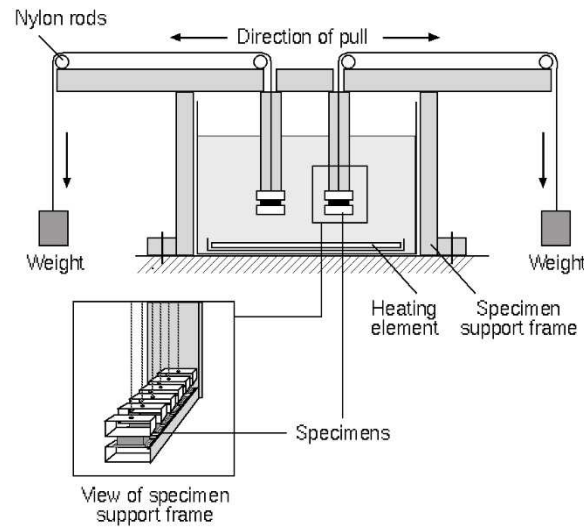


Fig. 12. Design of apparatus for applying hydro-thermal and mechanical stress to the adhesive-substrate interface through dead loads and hot water immersion [24]

It is important to note that all specimens that survived the exposure period yielded 100% cohesive failure in subsequent tensile tests. Also in the two cases where only one out of three specimens failed during immersion (40°C/0.16 MPa, 55°C/0.16 MPa), the tensile strength of the two surviving specimens (sealant cohesive strength) was measured to be well above the applied dead load stress.

This indicates that the failures (interfacial delamination) during immersion occurred at stress levels well below the cohesive strength of the sealant, confirming that the failure must have initiated adhesively, i.e. at the

sealant/substrate interface, although at later stages it may have propagated partly cohesively during the failure process.

These results also show that mechanical stress, when applied above a certain threshold, appears to encourage the degradation of the adhesive bond at the adhesive/substrate interface more than elevated water temperature. For example, increasing water temperature at loads of 0.04 and 0.16 MPa did not significantly increase the level of failures. However, increasing the interfacial stress for water temperatures of 40 and 55°C led to progressively higher frequencies of interfacial delamination. The final important observation to be made is that the failures that occurred during immersion did so within about 24 hours.

Table 1. Results of initial constant stress experiments to determine the relative effects of load and water temperature (tests done in triplicate on DC 795/anodized aluminium specimens). Control result – 0/0.94^a [24]

Water temperature °C	Dead load stress, MPa			
	0	0.04	0.16	0.22
20	–	–	0/0.73 ^a	0/0.70 ^a
40	–	0/0.49 ^a	80/26 0/0.72 ^a	60/24 70/7 80/26
55	0/0.76 ^a	0/0.66 ^a	80/24 0/0.65 ^a	70/2 80/3 40/24
70	0/0.56 ^a	–	0/0.49 ^a	–
20 (without immersion)	0.94 ^a	–	–	0/0.91 ^a

^a These results represent the average percentage adhesive failure/ultimate tensile strength (MPa) for samples that were tested immediately after surviving the 7-day exposure to the stated conditions. All other data represent the individual results for samples that failed during immersion, as percentage adhesive failure/time to failure (h). Coefficient of variation for tensile tests is 10%.

On the basis of the above initial results, it was decided that the tests would be conducted at the one temperature of 50°C, and that the constant interfacial stress would be increased in discrete steps until failure occurred within 24 hours. This critical stress would constitute the test result and should discriminate the relative adhesive behaviour of the adhesive/substrate system.

However, a technique for conducting the procedure had to be found that minimised the amount of testing required and yielded a statistically precise result. Simply increasing the stress in steps and testing multiple samples at each step was considered unsatisfactory for various reasons. It would only identify the performance range of a particular system and not provide for more precise discrimination. Also to achieve accurate discrimination would require small steps and therefore an unacceptable amount of testing.

Therefore a particular statistical procedure known as the “Dixon up-and-down method for small samples” [24] was applied. This method requires that initially the broad critical performance range be determined by conducting single specimen tests and increasing the load stepwise until failure occurs. A further sequence of tests, also on single specimens, is then performed within this critical range but using smaller load increments. On the basis of preliminary tests, and in order for the tests to be relevant to the structural use of sealants, the two stress step increments selected were 0.07 MPa and 0.014 MPa. Fresh specimens were used for each test (i.e. specimens that did not fail were discarded). The details of the technique are described in Reference [24].

6. Results

6.1. Tensile performance of unexposed (reference) specimens

All the substrates listed in Section 5.1 were subjected to the following treatments prior to adhesive bonding with Dow Corning 795 silicone adhesive:

- no treatment
- flame oxidation
- surface-grafted silane molecular brushes (0.25% amino-silane Z-6020: after flame-oxidation) [20].

Also the anodised aluminium (K1) and stainless steel (SS 304) substrates were silane-primed without prior flame “treatment”. These substrates already have surface –OH groups and hence were expected to exhibit adequate reactivity with the silane molecules without oxidation. For comparative purposes the organic substrates were also primed with the silane solution, although in this case the silane molecules will be attached to the surface due to the absence of active –OH and –COOH groups. After a 2 month cure, the specimens were tested in order to determine the stress at failure and interfacial failure mode. The tensile strength of all specimens was approximately 680 ± 50 kPa, and is thus not presented in graphical form.

However, an analysis of the failure mode (see Fig. 13) showed significant differences in the performance of the bare interfaces versus those grafted with amino-silane molecules. A particularly noticeable difference is observed with the PVDF-coated substrate D2. This substrate delaminated completely from the silicone sealant when untreated, but exhibited excellent adhesion after surface grafting with amino-silanes (100% cohesive failure in the sealant). Historically many PVDF type coatings have been excluded from high-rise building applications due to adhesion problems which could not be alleviated by the use of traditional primers.

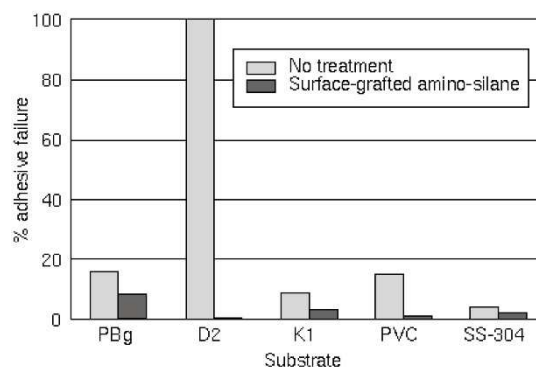


Fig. 13. Comparison of the levels of interfacial delamination of the silicone adhesive-substrate interface for a range of substrates with and without surface grafted amino-functional silane molecules (0.25% Z-6020 silane) and without accelerated exposure prior to tensile testing: PBg – Polyester powdercoat; D2 – PVDF coating; K1 – anodized aluminium; SS 304 – stainless steel

The other polymeric substrates, PBg and PVC, also exhibited significantly improved performance after surface-modification with surface-grafted silane. As expected the untreated stainless steel and anodised aluminium substrates, SS304 and K1, exhibited good adhesion to the DC795 silicone adhesive. As shown in Fig. 13, the presence of reactive connector molecules (amino-silane) further reduces the level of interfacial delamination by approximately 50%.

6.2. Tensile performance of specimens exposed to water immersion (7 days, 20°C) without mechanical stress

A batch of specimens prepared as described in Section 5.3 was cured for 2 months and then subjected to hydrothermal stress by 7-day water immersion at 20°C. Because of bond cleavage between the substrate and silicone molecules, it was expected that water immersion would degrade the quality of adhesion in those systems involving substrates which were either untreated, or only flame treated.

After water immersion at room temperature the specimens were tested in order to determine failure stress and interfacial failure mode. The results of this experiment are graphically illustrated in Fig. 14, which shows the level of adhesive failure between the substrate and silicone adhesive.

Generally, apart from PVC, the untreated substrates showed significant levels of adhesive delamination. For the polymeric substrates (PBg, D2 and PVC) flame oxidation alone, and also in conjunction with the surface grafting of the silane, resulted in a significant reduction in the levels of adhesive delamination after water immersion.

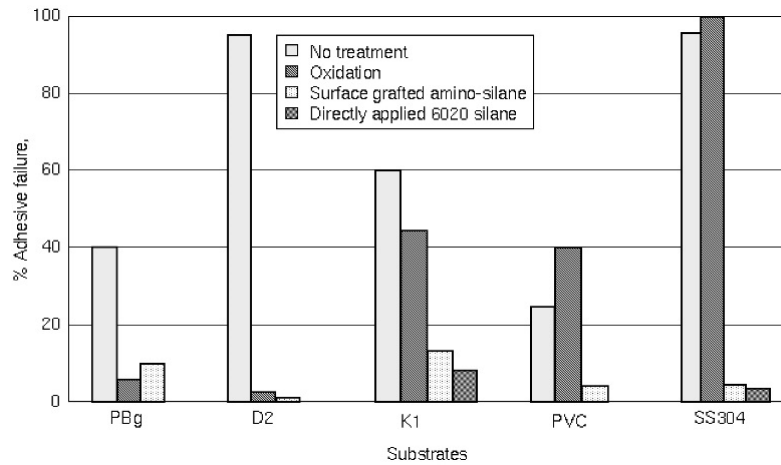


Fig. 14. Comparison of the levels of interfacial delamination of the silicone adhesive-substrate interface (after 7-days water immersion at 20°C but without mechanical stress prior to tensile testing) for a range of substrates with and without surface grafted amino-functional silane molecules (0.25% Z-6020 silane): PBg – Polyester powdercoat; D2 – PVDF coating; K1 – anodized aluminium; SS 304 – stainless steel

As expected, in the case of the metallic substrates, K1 and SS-304, the application of silane without oxidation considerably reduced the levels of adhesive delamination. Oxidation followed by silane application did not appear to offer any further advantage.

6.3. Tensile performance of specimens subjected to simultaneous mechanical and hydro-thermal stress

The range of specimens, described in Section 5.3 were exposed to a combination of mechanical and hydrothermal stress in order to assess the hydrothermal stability and durability of the interface under such conditions. The test protocol used is described in Section 5.4 and the results are shown in Fig. 15a and 15b.

The results for the polymeric materials show that the percentage levels of adhesive delamination (Fig. 15a) are reduced to some extent by flame oxidation only, but significant further reductions are evident after surface grafting with silane connector molecules: PBg – 88% (U/T: untreated substrate) to 38% (S/O: surface oxidation only) to 13% on surface grafted (S/G) substrate; D2 – 100% on U/T, 75% on S/O to 18% on S/G substrate; and PVC – 86% on U/T to 75% on S/O to 16% on C/G substrates.

For the anodised aluminium substrate (K1) oxidation alone, as would be expected, does not offer any advantage, as indicated by the similar levels of silicone adhesive delamination for both the oxidized and untreated substrates. The application of silane only to anodised aluminium surprisingly yields a small

improvement in adhesion levels (compare 90% for U/T to 70% for S/T (silane only treated; without pre-oxidation)). However the anodised aluminium surfaces treated with a combination of silane and flame-oxidization (S/O + silane) results in a significant reduction in interfacial delamination from 70% for S/T to 20% achieved on S/O + S. A study is under way to examine the mechanism for this improvement by investigating the surface chemistry of anodised aluminium with and without flame oxidation.

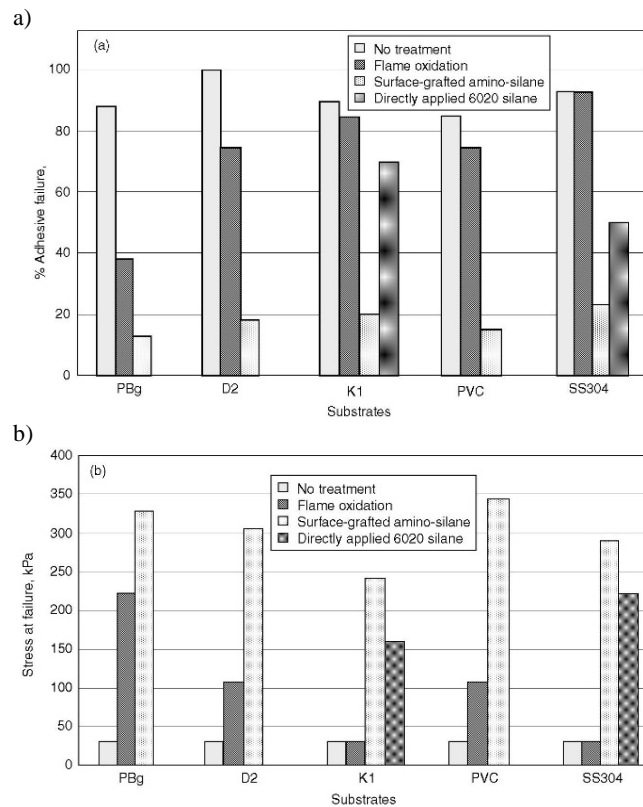


Fig. 15. Comparison of the performance of the silicone adhesive-substrate interface exposed to a combination of the mechanical and hydro-thermal stress prior to tensile testing, for a range of substrates with and without grafted amino-functional silane molecules (0.25% Z-6020 silane): PBg – Polyester powdercoat; D2 – PVDF coating; K1 – anodised aluminium; SS 304 – stainless steel: (a) percentage of interfacial delamination at the substrate-silicone adhesive interface and (b) stress of failure

For the stainless steel substrate (SS 304) the application of silane only reduces slightly the level of adhesive delamination (93% on U/T substrate, 50% on S/T). The combined silane/surface oxidation treatment further reduces the level of adhesive delamination to 23%, an outcome which will also form part of the

above study. One hypothesis is that the flame oxidation of anodised aluminium and stainless steel removes adsorbed contaminants more effectively than standard solvent cleaning, thus exposing more surface –OH groups for reaction with the silane molecules.

Figure 15(b) illustrates the influence of the various surface treatments on the strength of the silicone adhesive-substrate bond as determined by the current method. These results further confirm the effectiveness of the combined treatment of oxidation and surface grafting when compared to either oxidation or silane application alone.

7. Conclusions

1. Modularisation methodology through sub-division of the entire system into principal system platforms and independent functional or stylistic modules enables a product's easy assembly and dis-assembly and when needed, its re-configuration and styling. This includes development of new product families using the same and/or re-styled modules.

2. A feasible technology comprising pre-oxidation of substrates (plastics, composites, metals, ceramics) followed by application of graft chemicals in the form of organo-functional silanes leads to drastic improvement of the strength and durability of adhesive bonds between typical engineering substrates and adhesives. This paper presents examples of our technology effectiveness focusing on elastomeric silicone adhesives typically used in curtain wall installations by building and construction industries in residential and commercial building applications.

3. The technology demonstrates elimination (or acceptable reduction) of the danger of adhesive delamination in structural bonding due to incorporation of durable covalent bonds between engineering substrates and structural adhesives. Due to this fact, the proposed technology can be feasibly used in engineering design of engineering structures due to the fact that nearly 100% cohesive integrity of adhesives under typical conditions of environmental exposure facilitates application of typical structural design protocols and methodologies based on commonly accepted design and mechanical engineering principles.

4. Surface modification of typical engineering substrate materials commonly used by manufacturing industries, as described in this paper, facilitates rapid assembly of automotive or building structures (the latter applied to decorative and/or functional cladding and vision panels bonding to curtain wall structures of high-rise commercial or residential buildings) by adhesive bonding.

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